Independence of fingertip force coordination to interference from common tasks

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Abstract

The purpose of this thesis was to investigate if the integrity of object lifting and holding with one hand can be affected by the use of the other hand, by speaking out loud, or by watching a similar object being lifted by someone else. One chapter examined if the performance of one hand lifting and holding an object could be influenced by the other hand lifting another object or performing resource-heavy tasks. Results suggest that the fingertip forces of one hand experience no overflow from the other's. The other chapter investigated how auditory processing or production could affect fingertip forces. This series of studies explored (1) if sound cues such as objects impacting on a table surface, or (2) if lexical cues of manual or lifting action such as words with lifting-relevant context, could prime the planning component of object lifting and, additionally, (3) if the production of speech can affect online force control when holding an object. Neither of the priming experiments showed any effect on planning forces. Regarding articulation, participants applied more force on the held object while speaking than when they silently read words, but context of the word showed no effect. This chapter's findings echo those of the first's; no significant overflow of auditory input or output, on fingertip forces. This chapter also examined the consequences of watching another person lift a variety of object sizes whilst participants were holding a similar object. They gradually decreased their grip force on the object, both when watching videos or a real person lifting similar objects. The combined results suggest that the phenomenon of action observation does not extend to physically executing force-related motor commands. Overall, this thesis discusses the findings which suggest that fingertip forces are (1) impervious to direct influence from speaking, using the other hand, and watching object lifting, as well as (2) considerably more isolated in terms of overflow than kinematic systems are.

Keywords :

Bimanual coordination, grip force, bimanual coupling, grasping, auditory priming, speech production, action observation, lifting, holding, fingertip forces

Dedication

I dedicate this work to Konstantina, without whom, I would have not truly known what it means to be cared for. To be loved. Without whom, this piece of work would not have been created. Thank you for illuminating my path, for sticking by me like a bright torch, especially in times when the darkness was too intense and I too clumsy, dragging you with me. Thank you for including me in your ‘tribe’ and showing me the significance of empathy and honesty. This thesis is a result of your influence, of your light. Thank you for caring and believing in me through those difficult years.

This is also for my daughter, Madeleine, who was always in my heart throughout my long testing sessions away from home. The thought of you made everything brighter and a little closer to home.

You will always be my two girls to whom I dedicate my life.

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Darren Reid, my colleague, my friend, who went the extra mile and out of his way to help me out in times of need without a thought.

Thank you all for your friendship. You have marked me forever.

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1. **Chapter 1:** General Introduction

We are humans living in a world that is dominated by functional and essential objects to our wellbeing, and most are used for communication and facilitation of everyday modern life. We spend a substantial amount of time handling and manipulating objects with such skill that allows for other functions and behaviours to be performed simultaneously. This thesis is compiled to test whether interaction with objects can be affected by such functions and behaviours that we frequently perform in our everyday lives. Specifically, a series of studies are designed to test if the force we use to lift and hold an object securely in our grasp can be affected by a variety of concurrent tasks. It is important to understand possible limitations in our otherwise successful grip because these can potentially introduce a manual disadvantage in the manner that we hold and use objects and tools.

Typically, upon contact with an object, the forces that must be coordinated for a successful lift are 1) grip force (GF), defined as the force applied normal to the surface of an object and 2) load force (LF), defined as the force applied tangential to the surface of an object (Flanagan & Wing, 1993). There are a few ways available that can be used to lift an object such as using a power grip or a precision grip. A power grip resembles the way we grip a lever to manipulate it, while a precision grip involves the use of the thumb and one of the digits of the same hand forming a precise, locking mechanism. While both of those methods are capable of yielding grip and load forces, a precision grip allows resolution of force in orthogonal components normal and tangential to the surface of the object. For the purposes of this thesis, participants will be using precision grips with index finger and thumb.

GF anticipates LF changes, with the latter reflecting the mass of a given object (Johansson & Westling, 1984). GF increases as friction is reduced because reduction of friction informs the holder, through tactile feedback arising from the cutaneous mechanoreceptors in our fingers detecting pressure and distortion, that the object is beginning to slip, and prompts for a compensatory mechanism to decrease the chances of dropping the object (Johansson & Westling, 1984). As force increases, skin becomes denser and increasingly difficult for the load to alter the skin's elasticity and be released from the grip. When moving an object from one point to another, grip force is constantly adapting to the updated force requirements imposed by the movement (Flanagan & Wing, 1993). The authors suggest that continuous, feedforward processing is an essential method of grip force planning. The same authors also examined how external, real-time load additions, on top of transporting an object between two points, affect grip force coordination (Flanagan & Wing, 1997). Indeed, the ratio between GF and LF is kept constant when additional weight is added to the object. Anticipation of the object's weight is driven by the predicted weight of the objects (Johansson & Westling, 1988) based on its size (Gordon, Forssberg, Johansson, & Westling, 1991a, 1991b) and identity (Gordon, Westling, Cole, & Johansson, 1993). There is a large body of research that illustrates how fingertip forces behave in a variety of tasks. Researchers have experimented with slippery surfaces (Flanagan, Wing, Allison, & Spenceley, 1995), single finger behaviour and force application (Johansson & Flanagan, 2009), transporting an object between places in different ways including oscillating movements of the arms as well as with various speeds (Flanagan, Bowman, & Johansson, 2006), or transferring one object from one hand to the other (Chang, Flanagan, & Goodale, 2008). Those in-depth studies on lifting objects demonstrated that GF is the result of a rapidly adaptive system. While LF is expected to change as a result of movement related actions (e.g. lifting upwards) with GF following closely, when LF variations are unpredictable (e.g. horizontal movement) then GF is increased and kept constant throughout the movement, as if to exclude any possibility of the object slipping (Flanagan & Wing, 1993). It is apparent that fingertip forces are a robust and partially automated system that relies on bottom up information for successful applications. But what type of information is salient to the sensorimotor system?

Usually, size and shape provide the necessary cues that inform our grasping system on how to approach, where to place index and thumb, and how dense the object may be. As a result, fingertips exert the minimum grip force necessary for a successful hold, appropriate for the assumed weight of the object, derived from its density, which in turn was derived from its size and identity. Identity of an object, besides the memory of an object's weight category, also includes cues that inform us of the material it is made of (Buckingham, Cant, & Goodale, 2009). In whole, previous knowledge of an object helps in recalling the memory of it which creates an internal representation of weight. It has been demonstrated that prior-knowledge can be adequate for correct fingertip force scaling when lifting an object with no online bottom-up information (Buckingham & Goodale, 2010). In the study, participants were allowed a one-second window to see the object in front of them, were deprived of visual feedback afterwards, and lifted the object relying only on what they briefly witnessed and their haptic feedback. The objects they saw throughout the study were of different sizes, however they lifted the same average-sized object at all trials. This study demonstrated how those formed expectations of weight governed GF in the absence of direct, visual cues at the moment of grasping and lifting. Indeed, participants used higher force rates, both GF and LF, when they were expecting the object to be larger, thus heavier.

Expectations play a major role even when vision is used as a guide for weight estimation. When we successively lift objects of identical appearance but different weights, the object we lifted last creates the weight expectation for the next (Johansson & Westling, 1984). In their study, the authors clearly illustrate how grip and load forces overshoot on a light object when that is preceded by a heavier one and vice-versa. Sensorimotor prediction appears to rely heavily on expectations of weight, which are in turn, formed due to experience. However, force correction on misjudged weights happens very rapidly, as demonstrated with vision-blocked participants expecting a certain weight, and when vision was unblocked the object was changed (Loh, Kirsch, Rothwell, Lemon, & Davare, 2010). Motor system excitation showed that it registered this sensorimotor change as early as 150ms after visual input of the new size, requiring an updated internal model of weight representation.

If perceptual input is capable of influencing sensorimotor prediction, and the latter is in turn influencing grasping kinematics and fingertip force scaling, such as force application rates, then certain types of tasks may be capable of influence as well. It is still unknown if a constant grip force application can be affected by the other hand's actions, especially when that hand is lifting another object or performing a common task unrelated to the task the other hand is occupied with. Additionally, it is important to examine whether auditory processing, speech production, and observing action can also influence grip force, or if fingertip forces parameterise their behaviour independently, unaffected by either the use of the other hand or by auditory and visual influences. Interesting findings come from a recent study where participants held a cylinder and listened to words played back to them (Frak, Nazir, Goyette, Cohen, & Jeannerod, 2010). When the word was action-related, they observed a modulation of grip force when compared to nouns. There is also substantial evidence from a fingertip force application study that examine how cortico-spinal excitation is modulated when participants are watching another individual lift various objects that differ in size and mass from the participant's; the higher the size observed, the higher the degree of excitation (Buckingham, Wong, Tang, Gribble, & Goodale, 2014).

The phenomenon of 'action observation' has been theorised to be a manifestation of mirror neuron functions. Specifically, the role mirror neurons are believed to play in 'action understanding'; understanding an observed action and retrieving it to allow its execution (Pellegrino, Fadiga, Fogassi, Gallese, & Rizzolatti, 1992). There is an active, ongoing debate on the role of mirror neurons in the sensorimotor system. One side suggests that mirror neurons are coding for action understanding (Rizzolatti & Craighero, 2004) and are the primary means of recognising actions performed by others. The theory has been refined as an umbrella term that describes a system of mirror neurons, responsible for understanding action and intention, producing speech and imitating action (Fabbri-Destro & Rizzolatti, 2008). The other side disagrees with the interpretations and asserts that the evidence so far does not allow for a specific attribution such as 'action understanding', but proposes that understanding action can still be acquired without the involvement of mirror neuron systems (Hickok, 2009). Regardless of the neural correlates where this behaviour arises from, it is important to understand the behavioural extent of its impact on the sensorimotor system.

These factors reflect everyday common actions and behaviours that we perform very frequently, often automatically, while lifting or holding items, such as talking, listening, watching someone lift an object, or use our other hand for a similar or different purpose. These items could range from a cup of coffee to a scalpel held by a surgeon. Little is known on the direct effects, if any, that using the other hand, speaking out loud, or watching someone perform a manual action, can have on the fingertip forces applied by our precision grip onto a held object.

The 4 experiments of Chapter 2 are exploring how one hand's fingertip forces can affect the otherwise consistent static fingertip forces of the other hand on a holding object. Static fingertip forces on a holding object are also examined when the other hand is performing object lifting related or unrelated tasks to see whether the type of task plays a role in a potential force interference between the two hands.

The 5 experiments of Chapter 3 however are focused on how fingertip forces are planned and controlled between one holding hand and language comprehension, speech, and action observation. Specifically, if language related to lifting can prime fingertip forces, and if vision related to lifting can do the same.

2. **Chapter 2:** Fingertip forces between hands – Independent or co-dependent?

2.1 Introduction

We more often than not use both our hands to perform common tasks. Usually some of these tasks require different actions for each hand, yet we are still successful in coordinating both our hands to act simultaneously, facilitating our performance towards the end result. However, while they seem to act smoothly in such cases, there are factors that can influence their performance. The purpose of this chapter is to examine if this influence is strong enough to pose a significant constraint in common, everyday actions.

When we reach and point at targets bimanually, the hands exhibit a degree of temporal synchrony. For example, even if both hands are making reaches of different amplitudes, they both appear to start and end their movements simultaneously to the common observer. This behaviour has been noted in a wide range of different bimanual contexts to date with subjects i.e. pointing on different targets (Sherwood, 1994), using styli (Fowler, Duck, Mosher, & Mathieson, 1991), using styli of varying weights between hands (Marteniuk, MacKenzie, & Baba, 1984), and reaching to grasp objects (Jackson, Jackson, & Kritikos, 1999). Recent work examining bimanual reaching showed asynchronous movement onset and movement end times when the targets were located at different distances from the body (Riek et al., 2003). Additionally, in the spatial domain, short movements were on average overshot when the other hand performed a long reach, and long movements were undershot when the other hand performed a short one, when compared with the control condition where both hands reached for targets placed at the same distance from each hand's starting point (see also Spijkers and Heuer 1995).

To examine bimanual temporal asymmetries between hands, Buckingham et al., 2010, had participants perform contralateral unimanual reaches, and equivalent bimanual reaching with an ipsilateral-reaching counterpart. In their task, the right hand reached toward targets at different distances in the right side of space while simultaneously the left hand reached at a fixed target on the right space. The left hand's contralateral reach showed decreased movement times (MTs) when the right hand performed a concurrent reach into ipsilateral space, compared to when reaching alone. The opposite configuration – right hand reaching in contralateral space with the left hand performing a concurrent ipsilateral reach – showed no differences in MTs when compared to the unimanual condition. The authors noted that the left hand's performance was improved when the right hand was present, and provided support to the notion that control of the left hand is yoked to the right. A number of studies have demonstrated that bimanual reaching-to-point performance is subject to asymmetries, both in the spatial and the temporal domain (Fowler et al., 1991; Koeneke, Lutz, Wüstenberg, & Jäncke, 2004; Marteniuk et al., 1984; Marteniuk, Leavitt, MacKenzie, & Athenes, 1990), in contrast to the original notion that bimanual movements begin and end their movements in perfect synchrony (Kelso et al., 1979).

A series of experiments investigating hand trajectories while participants reached for targets examined this phenomenon and how it manifests spatially (Kelso, Putnam, & Goodman, 1983). The authors placed an obstacle between one hand and its target and during a bimanual reach toward target pairs, and observed that for some participants the unobstructed hand made a slight (unnecessary) vertical elevation in space, presumably caused by the hand reaching over the obstacle. In a more recent study, participants reached toward visual targets with unimanual and bimanual reaches while one of the targets was displaced mid-trial (Diedrichsen, Nambisan, Kennerley & Ivry, 2004). The hand moving to the displaced target corrected its trajectory, but in almost all cases the hand moving to the stationary target performed a minor yet significant perturbation of its trajectory in the same direction as the other hand. The authors ruled out any biomechanical factors through additional kinematic measures and suggested a modulation of the motor command issued to the hand moving towards the stationary target. Most importantly, evidence suggests that task demands play a major role in how temporal and spatial coupling is manifested during bimanual coordination (Mason, 2008; Mason & Bruyn, 2009).

Although spatial coupling between hands happens in a lot of cases during bimanual reach-to-point tasks, it is less clear whether this coupling may also be present in the grasping system. The peak grip aperture (PGA) is used in the literature as a variable that reflects the distance between index finger and thumb. Typically when grasping an object, participants adjust their PGA wider than the distance of the planned contact points on target objects, and always in proportion to an object's size (Jeannerod, 1984). It has been shown that bimanual reach-to-grasping tasks cause a reduction in peak velocities and an increase in MTs of the reaching phase, in addition to wider PGAs of both hands compared to unimanual tasks (Jackson, Jackson & Kritikos, 1999). The authors noted that each hand independently scaled grip aperture to the size of the target object. In other words, even though the parameters of the reach were synchronised, the grip aperture profiles were significantly different from each other during a bimanual reach, providing evidence that the grip aperture is parameterised independently for each hand. They have demonstrated, however, a slight cost of bimanual grasping, shown by a proportional increase of PGA of both hands in a bimanual condition when compared to equivalent unimanual grasps. This effect could be ascribed to an increase in task difficulty rather than to an influence of one hand over the other, as there was no bimanual asymmetry, namely yoking, between PGAs. Recently, a study demonstrated that when participants reached, grasped, and transported cylinders of either congruent/incongruent sizes or congruent/incongruent target locations, they showed spatial coupling for congruent conditions and independent upper limb performance for incongruent conditions (Mason & Bruyn, 2009). Specifically, some temporal coupling was observed for the transport component, while spatial measures of the grasping component, such as PGA, suggested a low degree of spatial coupling in both congruent and incongruent conditions. They speculated that coupling may be present in situations where it can facilitate performance such when both hands act on the same parameters under a shared command, and not present when it can hinder performance, e.g. when each hand requires a specific set of commands for its respective task's parameters.

It is important to clarify the distinction between reach-to-point and reach-to-grasp tasks which partially illustrates why fingertip forces are treated as an independent sub-system rather than an equally sensitive component of a reaching action. While the reaching component's neural substrate activation overlaps the grasping component's (Filimon, 2010), there do appear to be networks which code for one task but not the other. Specifically, grasping shows a higher degree of activation when compared to a pointing task (Pierno et al., 2009). For example, the anterior intraparietal sulcus (aIPS) shows activation in reach-to-grasp tasks, and is also activated in grasping tasks that lack the reaching component. Additionally, the superior parietal lobule (SPL) shows overlapping activation during grasping and in reaching tasks (Castiello, 2005), but a higher degree of activation in those grasp related areas when compared to a reaching-to-point task (Cavina-Pratesi et al., 2010). This distinction was also shown behaviourally, earlier, in a reaching-to-point versus reaching-to-grasp study (Carnahan, Goodale, & Marteniuk, 1993). In one of the conditions the targets were perturbed during the trial, forcing an online reach correction in order to localise the target. The parameters of the reach ('peak velocity' and 'time to peak velocity') were different when pointing than they were when reaching to grasp.

Both tasks rely on target localisation, and a goal directed movement towards that target. This planning phase is reflected on grip and load force rates that are calculated at the earliest point of the lift. Those are variables that show the very early expectations of weight, and could reveal asymmetries between hands in the planning phase if any. Online fingertip force control, the subsequent phase of having grasped and actively holding an object, will be inferred from the analysis of this consistent, static application of force, and its sensitivity to the other hand's actions. To simplify, since there is yoking between hands in reach-to-point tasks but none observed in grasping tasks through PGA data, examining forces in similar manipulations could inform us whether forces behave independently like PGA, or yoked together like reaching components.

So far, one theory proposes that components of a reaching and grasping movement are distinct and operate independently (Jeannerod, 1984). The author closely examined a reaching movement towards an object, with the final goal being grasping and lifting; two phases were identified. A fast velocity phase where the hand is moving towards the object with fingers stretched and forming a grasp, and a subsequent lower velocity phase beginning at approximately 75% of the movement duration. At that point, fingers were already in formation and started to close, expecting proximity with the object. The 75% margin remained consistent, both when visual feedback of the limb was available and unavailable, and at different target distances. The author argues that the phases of sensorimotor prediction (reaching to grasp) and online force control (grasping) are distinct facets with different automated mechanisms for each. In a later study, the distinction between planning and control is well illustrated (Glover & Dixon, 2002). Participants reached to grasp an object that depicted the words "small" or "large" on it. While the object remained unchanged in both conditions, the size-related words affected the planning phase; PGA scaled proportionally to the size described. However, as distance to the object was decreasing, PGA was decreasing linearly to the object's true size. The findings suggest that when online control is required to operate, higher-order perceptual processes provide less relevant information to the sensorimotor system.

This thesis is also drawing a parallel between the kinematic parameters observed in reach-to-point tasks and the kinetic (related to forces) parameters in lifting. Specifically, the aim is to determine whether planning, online control, or both of these facets of lifting are operating with different sensitivities and interactions than those that govern reaching tasks. To date, no studies have examined how individuals coordinate their online control and planning of fingertip forces when lifting objects with both hands simultaneously. It is hypothesised that since motor control involves the arm as well as the hand, fingertip forces may behave in a similar manner to kinematics when it comes to targets positioned symmetrically or asymmetrically from the subject. For example, it is expected that when lifting masses presented asymmetrically to left and right hands; the hand that lifts the lighter mass will overshoot its fingertip forces due to the other lifting a heavier mass. Similarly, it is expected that the hand lifting the heavier mass will, on average, undershoot due to the other hand lifting a lighter mass. No change is expected to be seen when both lift the same masses. This prediction is based on the reaching-to-target literature that highlights this phenomenon (Barthelemy & Boulinguez, 2001; Buckingham & Carey, 2008; Buckingham, Main, & Carey, 2011; Byblow, Chua, & Goodman, 1995; Mason & Bruyn, 2009; Neely, Binsted, & Heath, 2005; Rogers, Bradshaw, Cunnington, & Phillips, 1998) and as such we predict that the control of forces may show a similar bimanual asymmetry as hand kinematics.

The closest relevant study which has investigated grip force control in the context of unimanual object lifting found no asymmetries in either sensorimotor prediction or fingertip force adaptation between the dominant and non-dominant hands (Buckingham, Ranger, & Goodale, 2012). Subjects reached and lifted cubes of different sizes and weights, often incongruent weights relative to their size (e.g. larger cube was lighter than the smaller cube). As a result, GF was rapidly corrected in the incongruent trials, similar to the correction observed in the congruent trials, regardless of hand dominance. The authors conclude that hand dominance did not influence the interlimb transfer of information, suggesting that fingertip forces should be included in theories of cerebral laterality such as control overlap (Kelso et al., 1983) or neural cross-talk (Marteniuk et al., 1984). The goal of the current work is to examine (1) whether fingertip forces are parameterised independently for each hand, and (2) whether the fingertip forces of one hand can be influenced in the direction of the other hand's actions, akin to motor overflow. In this thesis, motor overflow is regarded as the phenomenon when the balance of inter-hemispheric coordination of motor information is skewed towards one side, and the resulting motor commands of one arm are modulated by the overflown motor commands of the other (Liederman & Foley, 1987). Additionally, it is investigating if this parameterisation differs between the aspects of planning and control during object lifting. To this end, various grip and load force parameters are examined in a bimanual context and are compared to equivalent unimanual lifts. The planning phase is operationalised through the rates of GF and LF changes, while the control phase through GF and LF peaks, as well as static GF (the average GF measured at the holding-still phase of a lift). The first experiment is investigating whether one hand's grasping and lifting performance is influenced by the other hand performing the same task. It is anticipated that, in line with reach-to-point performance, each hand will perform similarly in both conditions; bimanually and unimanually. In the second experiment, it is asked if lifting different weights with each hand shows yoking between them. In the third experiment, the thesis examines whether a hand which is already holding an object can have its static holding force influenced by the other hand's lift. Finally, the fourth experiment explores how one hand's static holding force can be influenced by its counterpart performing a range of non-lifting motor tasks, such as tapping or typing on a keyboard. 'Static' is the term given here to the consistent application of grip force over a period of time on an object. Depending on specific experimental protocols, static force will reflect an average force value drawn from a pre-defined section within a holding phase.

2.2 Experiment 1: Lifting even weights

2.2.1 Methods

Participants

A total of 18 self-reported right-handed individuals (mean age 23.6 years, SD=4.7, range from 19-35) were recruited from Heriot-Watt University, Edinburgh, comprising 7 males and 11 females. Assessment of handedness was performed online as a follow-up with the use of Edinburgh Handedness Questionnaire. All participants had normal or corrected-to-normal vision and no motor impairments. All participants gave informed consent prior to testing, and all procedures were approved by the local ethics board.

Stimuli and procedure

A custom-written script in MATLAB (Mathworks) controlled the trial start and end cues with a short "beep", and handled the data collection from a pair of force sensors (Nano17, ATI Tech). A pair of PLATO shutter goggles (Translucent Technologies) were used to allow participants' vision only for the duration of each trial which lasted for four seconds. The shutter goggles ensured that the participants would not witness the experimenter moving the objects around between trials, to avoid being influenced by the apparent weight and hand kinematics, and to standardize the object's exposure duration.

The stimuli were two identical black plastic cylinders of equal mass (400 grams) and equal volume (7.5 cm diameter, 7.5 cm tall), placed on noise-dampening green felt pads. The force sensors were mounted on top of each stimulus attached to a custom-made handle (Figure 1a).

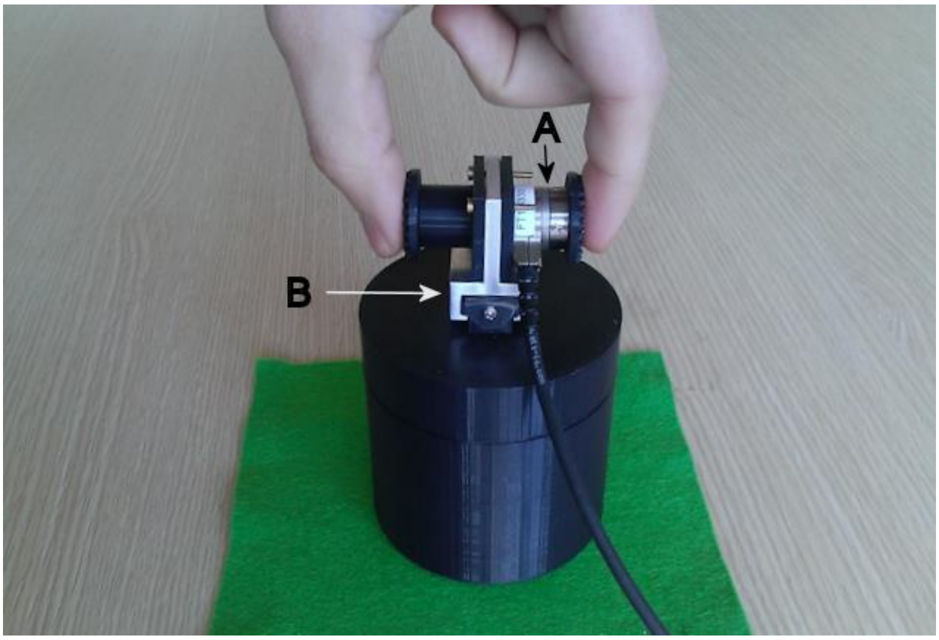

Figure 1a. Image showing the A) force sensor attached on a B) custom-made handle that is mounted on one of the stimuli

Participants sat on a chair in front of a large table and placed their hands on it in a relaxed manner, barely touching a plastic button attached to the edge with their index fingers, palm resting on the table. The button served as a start and end-point for each trial. Stimuli were placed symmetrically the same distance from each hand (50 cm), along the midline of the body, 25 cm apart laterally (Figure 2). The participants were instructed to lift, without delay, whatever object was on the two felt pads; specifically, lift with their left hand if the left cylinder was present, with their right if the right was present, or with both hands if both cylinders were present. After the auditory cue, the goggles cleared and participants reached toward and lifted the stimuli to a marked height (approximately 23 cm), and held them steady until the second beep sounded and then returned the objects to the table surface. Participants were instructed to lift the object(s) by grasping the handle on top of the object with their thumb and index finger forming a ‘precision grip’. This grip was practiced with a few trials before the start of the experiment for the subject to become familiarised with the technique. The goggles then closed and obscured the participant’s vision, at which point they placed the objects back to the felt pads. Each session featured 60 trials (20 Left hand, 20 Right hand, 20 Bimanual). Trials were presented in one of four random orders, and the experiment took approximately 20 minutes.

Sensors recorded 3D forces at 1000 Hz, and the data were smoothed with a low-pass Butterworth filter with a cut-off frequency of 14 Hz. The forces orthogonal to the surface of the grip pads (Z-axis) were defined as grip force (GF) and the remaining forces (X and Y-axes) were vector summed to yield load force (LF). These force vectors were differentiated with a 5-point central difference equation to yield grip force rate (GFR) and load force rate (LFR), the main indices of sensorimotor prediction, as these are variables that are measured at the earliest point of a lift. Then, the mean GF during the holding phase was calculated which was defined as the average GF between 2.5 to 3.5 seconds of each 4-second trial. This time-interval was selected based on observations that, on each trial, all participants had completed the lift and the object was being held static above the table surface (i.e., with no large deviations in load force). Additionally, to confirm the synchronicity of the lifts, the lifting onset was first identified as the timepoint at which LF was larger than 0.1 Newtons (N) for each hand. To determine whether lifting occurred synchronously left hand's load force onset time was subtracted from the right hand's and the resulting difference between hands was tested with a one-sample t-test against zero, because zero would indicate synchronicity between hands during force initiation. The rest of the dependent variables (GFR, LFR, and static GF) were analysed with a 2×2 repeated measures ANOVA each, with the factors of Hand (Left, Right) and Condition (Unimanual, Bimanual). A figure of overlapping force traces from same-weight trials across 7 participants is included to illustrate how a GF profile is depicted (Figure 1b). The highest peak is interpreted as the maximum GF.

Throughout experiments, the Bonferroni method is used for multiple comparison corrections, and when Mauchley's test of sphericity shows a violation, Greenhouse-Geisser corrections are used.

Error bars show the normalised error of the mean, a process that involves normalizing individual data by removing between-subject variance (Cousineau, 2005). To remove between-subject variance, the participant's mean score of all trials within a level is subtracted from each individual score, and the mean score of all participants is added instead. The resulting scores are scores which contain only within-subject variability. The standard error of these normalised data is then calculated which yields the normalised standard error of the mean. As it is expected, normalised standard error or the normalised data cannot be used for analysis and only serve as a visualization tool. Throughout this thesis, all figures feature normalised standard error of the mean bars.

Generalised eta squared (η_G^2) is used as a measure of effect size. The reasoning behind this choice is based on 1) the generalisability of η_G^2 to the population, and 2) being a recommended choice for within-subject repeated measures, compared to omega which is recommended for between-subject designs (Bakeman, 2005; Olejnik & Algina, 2003).

For the most part, this thesis is using graphs that depict all levels of the relevant variables rather than only the main effects for visualisation. This is because the main differences within any main effect are very small and a visual depiction would not add any further information.

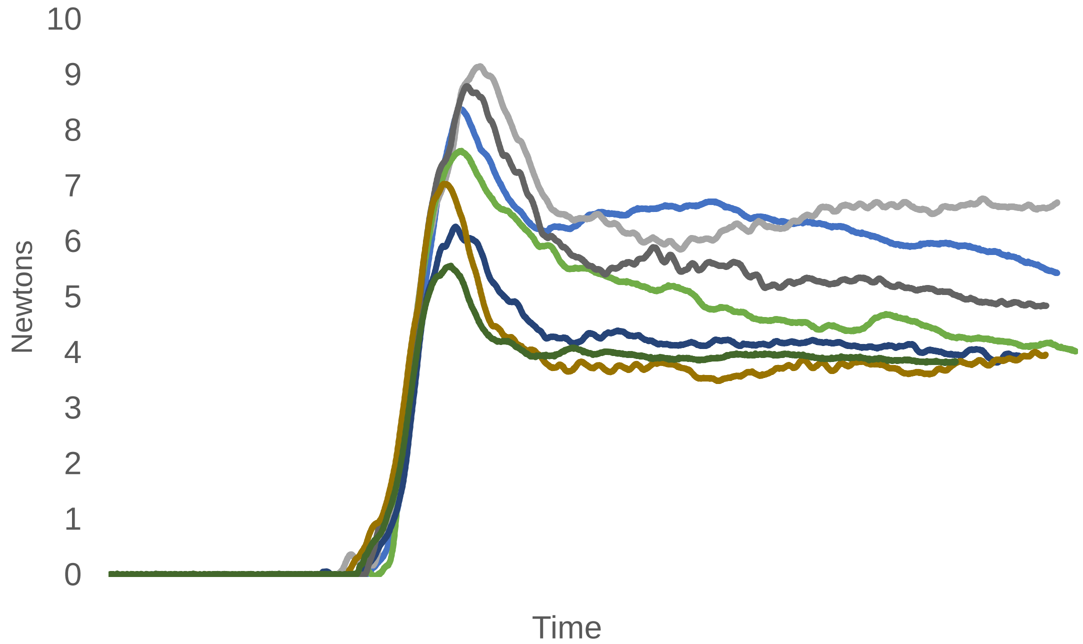

Figure 1b. The means of peak LFR values for each hand across conditions

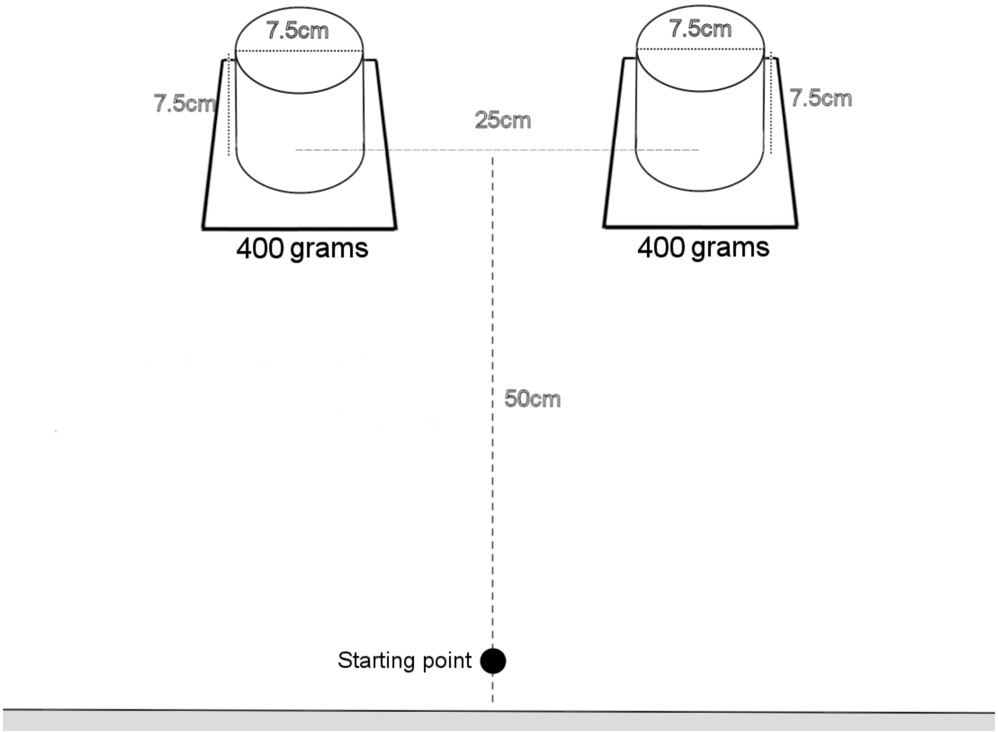

Figure 2. Schematic of the experimental setup of the table surface from the participant's perspective

2.2.2 Results & Discussion

Sensorimotor prediction

First, grip force rate (GFR) showed no differences between Condition ($F(1, 17) = 0.46$, $p = .51$, $\eta_G^2 = .012$) or between Hand ($F(1, 17) = 0.34$, $p = .57$, $\eta_G^2 = .001$), and no interaction between Condition and Hand ($F(1, 17) = 3.25$, $p = .09$, $\eta_G^2 = .118$; Figure 3), meaning that the rate of grip force application applied was similar between hands and conditions.

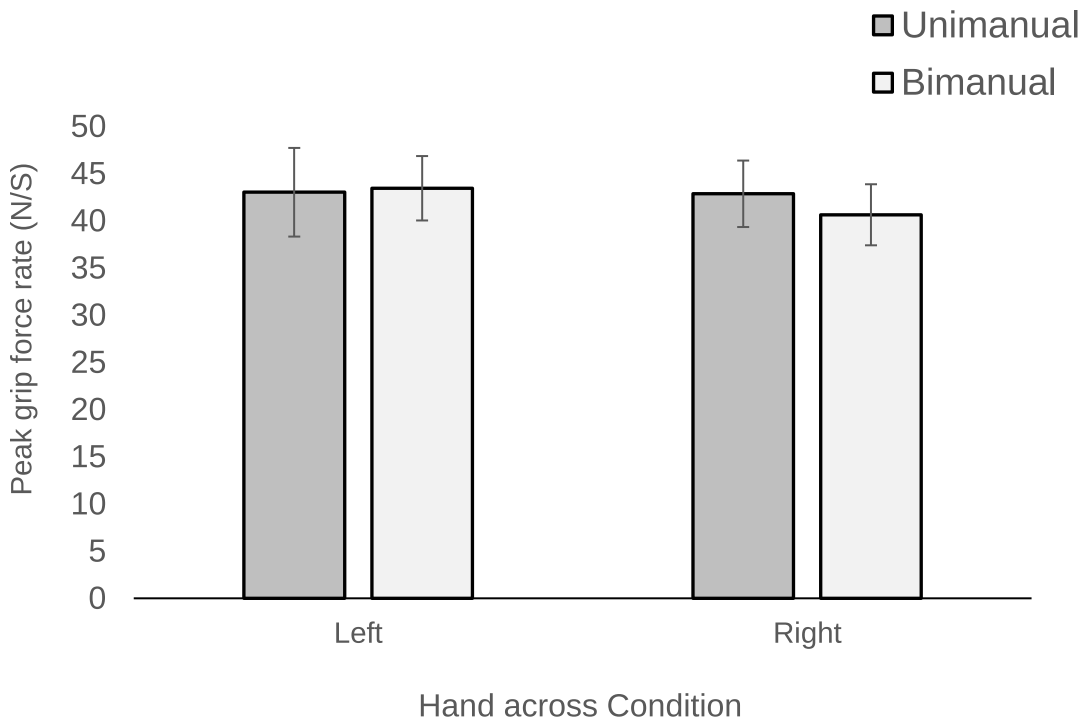

Figure 3. The means of peak GFR values for each hand across conditions. Error bars show the normalised standard error of the mean

There was no difference in the rate of load force (LFR) between hands (F(1,17) = 0.61, p = .44, η_G^2 = .024; Figure 4), but LFR was significantly higher in the unimanual condition compared to the bimanual condition (F(1, 17) = 5.25, p = .021, η_G^2 = .24; M = 36.18 N/S vs. 34.88 N/S). There was no interaction between Condition and Hand (F(1, 17) = 0.002, p = .96, η_G^2 = .004). This means that participants lifted the objects with a lower rate bimanually than when they lifted each in isolation.

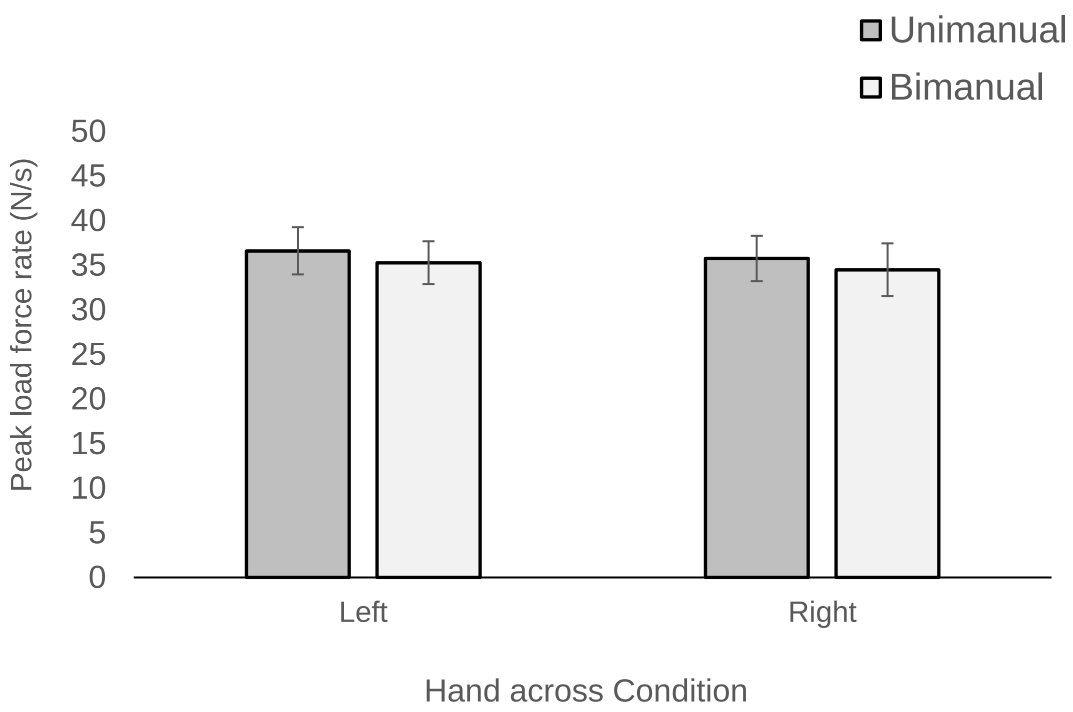

Figure 4. The means of peak LFR values for each hand across conditions

Then the temporal LF onset difference between hands in the bimanual condition (M = -13.3, SD = 21.9) was compared against zero, and no significant difference was found (t(18) = -0.017, *p* = .35), indicating that both hands started the lifting action simultaneously (Figure 5).

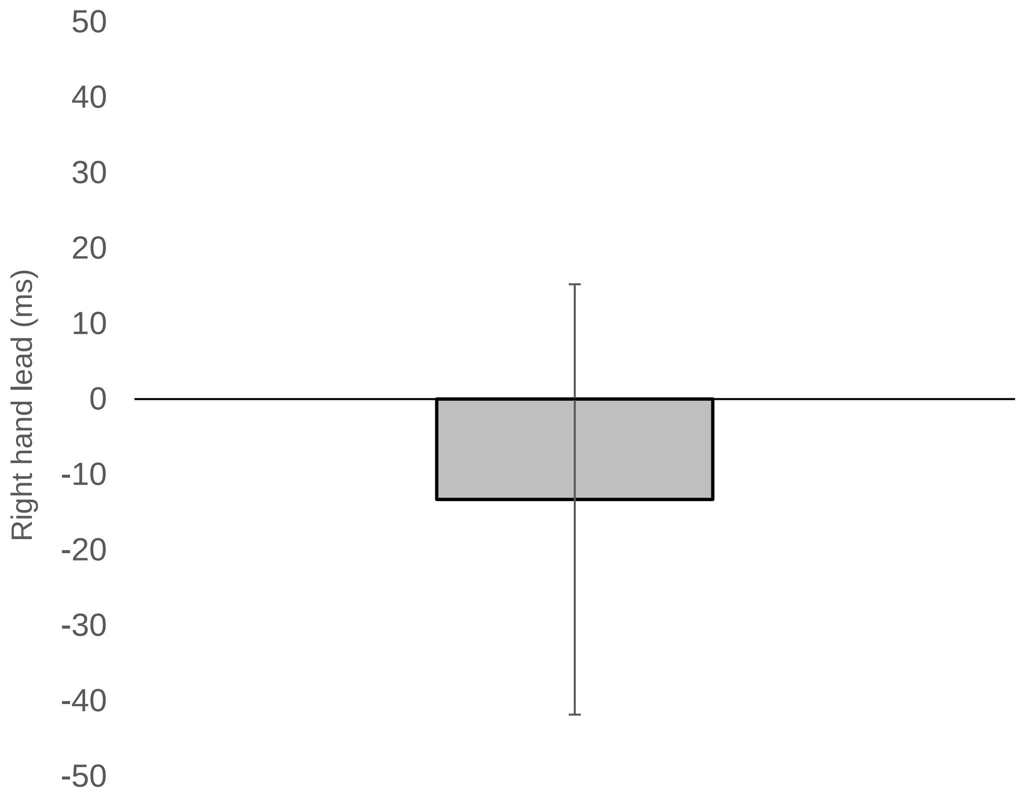

Figure 5. The mean difference between right and left hand LF onset. Positive values reflect an earlier right hand onset while negative values an earlier left hand onset. The difference was not significant

Online force control

Surprisingly, while both hands were hypothesised to perform similarly to their unimanual counterpart, bimanual static grip force (GF) was larger than unimanual static GF (M = 6.31 N vs. 5.98 N; $F(1, 17) = 6.64$, $p = .02$, $\eta_G^2 = .19$). There were, however, no differences between Hand ($F(1, 17) = 0.24$, $p = .62$, $\eta_G^2 = .008$; Figure 6) and no interaction between Hand and Condition ($F(1, 17) = 1.41$, $p = .25$, $\eta_G^2 = .054$).

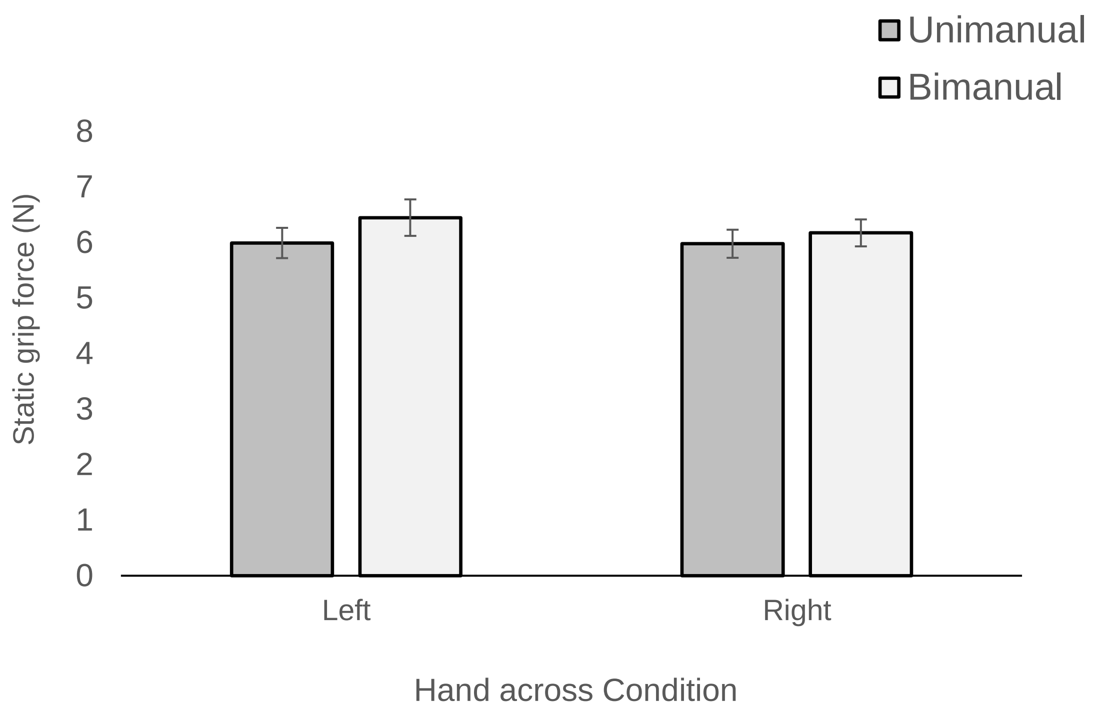

Figure 6. The means of static GF values for each hand across conditions

This experiment attempted to illustrate what happens to sensorimotor prediction and force control during a bimanual task when force demands were identical between hands. Specifically, it was expected that there would not be any differences in fingertip forces between any condition, as the tasks were identical between hands. Indeed, there was no difference in LF onset, indicating that both hands initiated their respective lifts simultaneously. In terms of force parameters, when participants lifted identical objects bimanually, the pre-liftoff peak grip force rates of the left hand did not differ from those of the right hand, meaning that there was no difference in the way participants grasped each object. However, unexpectedly, participants tended to hold the objects with more force when grasping in a bimanual context than they did in equivalent unimanual lifts. Furthermore, bimanual peak load force rate was lower when compared to the equivalent unimanual lifts, indicating a slower lifting action in the bimanual condition. These differences appear to reflect a “bimanual cost” akin to the one evident on preparation and movement time, as noted by other authors (Ohtsuki, 1994; Blinch et al., 2015).

2.3 Experiment 2: Lifting uneven weights

Next, to directly examine whether there is any evidence of bimanual force coupling or force yoking, individuals controlled their fingertip forces when lifting objects of a different weight with each hand. A design that can imitate an analogous situation with that of asymmetrical targets may offer additional insights in fingertip force parameterisation between hands and bimanual conditions. It is predicted that the hand lifting the heavy object would undercompensate its force application and the hand lifting the light one would overcompensate when these objects are both lifted bimanually.

2.3.1 Methods

Participants

A total of 21 self-reported right-handed individuals (mean age 24.3 years, SD = 5.3, range from 19-36) were recruited from Heriot-Watt University, Edinburgh, comprising 8 males and 13 females. Assessment of handedness was performed online as a follow-up with the use of Edinburgh Handedness Questionnaire. All participants had normal or corrected-to-normal vision and no motor impairments. Two participants took part in Experiment 1. All participants gave informed consent prior to testing, and all procedures were approved by the local ethics board.

Stimuli and procedure

The apparatus and procedures were identical to Experiment 1, with the exception that the stimuli which were still identical-looking black cylinders of equal size (7.5 cm diameter, 7.5 cm tall), but could weigh either 200 grams or 400 grams, and the force data was recorded at 500Hz. Each participant lifted the six hand/mass configurations (10 Left - Light mass, 10 Right - Light mass, 10 Left – Heavy mass, 10 Right – Heavy mass, 10 Bimanual Heavy(Left) – Light(Right), 10 Bimanual Light(Left) – Heavy(Right)) in one of four random orders, for a total of 60 trials.

Dependent variables including grip and load forces and their respective rates, were analysed each with a 2×2×2 repeated measure ANOVAs, Condition (Unimanual, Bimanual), Mass (Light, Heavy), and Hand (Left, Right).

2.3.2 Results & Discussion

Sensorimotor prediction

Analysis of GFR found no main effect of Condition (F(1, 20)= 1.8, p = .19, η_G^2 = .062), Mass (F(1, 20) = 0.5, p = .46, η_G^2 = .017), or Hand (F(1, 20) = 2.44, p = .13, η_G^2 = .096; Figure 7). Furthermore, there was a significant interaction between Condition and Hand (F(1, 20) = 7.04, p = .015, η_G^2 = .226). Multiple comparisons revealed that the Left Hand had a higher GFR than the Right in the Bimanual Condition (M = 46.49 N/s vs. 40.51 N/s; t(41) = 3.21, p = .003), and that the Right Hand showed a higher GFR in the Unimanual Condition when compared to the Bimanual Condition (M = 44.47 N/s vs. 40.51; t(41) = 3.1, p = .004). No interaction was observed between Condition and Mass (F(1, 20) = 0.02, p = .87, η_G^2 = .003), Hand and Mass (F(1, 20) = 0.28, p = .6, η_G^2 = .005), or Condition and Hand and Mass (F(1, 20) = 0.13, p = .71, η_G^2 = .006).

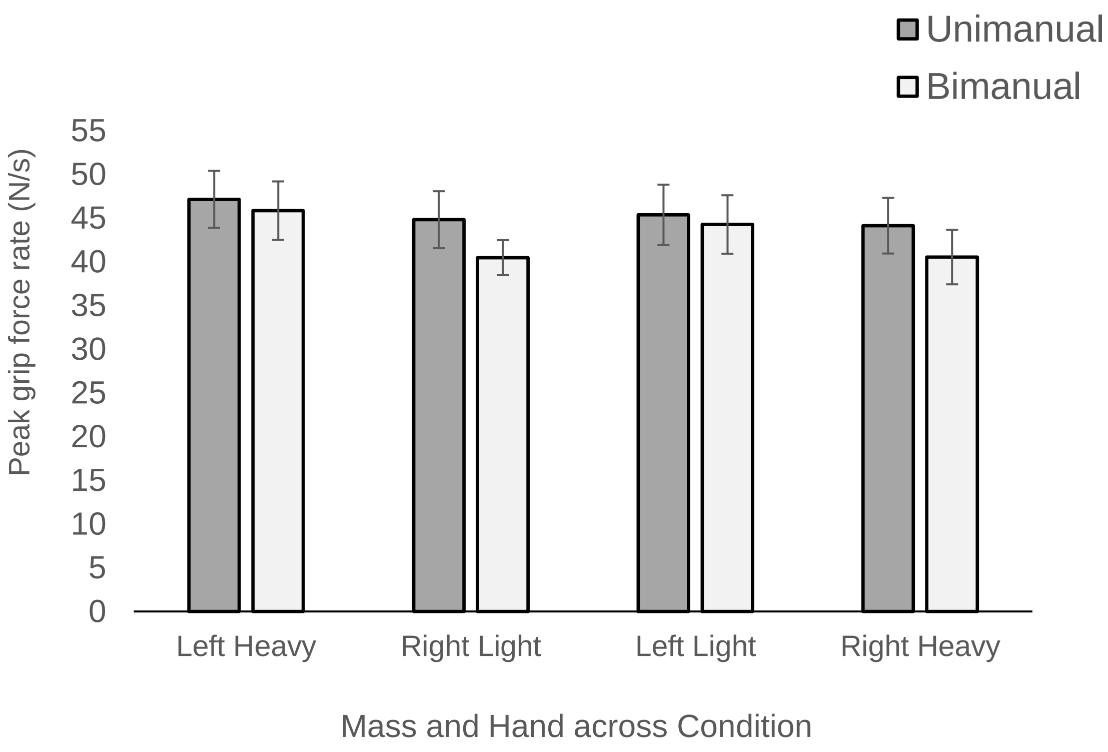

Figure 7. The means of peak GFR values for each hand across conditions

In contrast to GFR, peak LFR showed a main effect of Mass (F(1, 20) = 12.45, p = .002, η_G^2 = .289; Figure 8). This is likely because the objects weighed different amounts from one another, and load force parameters are more closely linked to object mass than grip force parameters are. As with GFR, there was no effect of Hand ($F(1, 20) = 3.26$, $p = .09$, $\eta_G^2 = .098$), but Condition was marginally significant showing a trend ($F(1, 20) = 4.25$, $p = .053$, $\eta_G^2 = .128$). No interaction was found between Hand and Mass ($F(1, 20) = 0.04$, $p = .84$, $\eta_G^2 = .004$), Hand and Condition ($F(1, 20) = 1.63$, $p = .22$, $\eta_G^2 = .003$), Mass and Condition ($F(1, 20) = 1.29$, $p = .27$, $\eta_G^2 = .004$), or Hand and Mass and Condition ($F(1, 20) = .06$, $p = .81$, $\eta_G^2 = .001$).

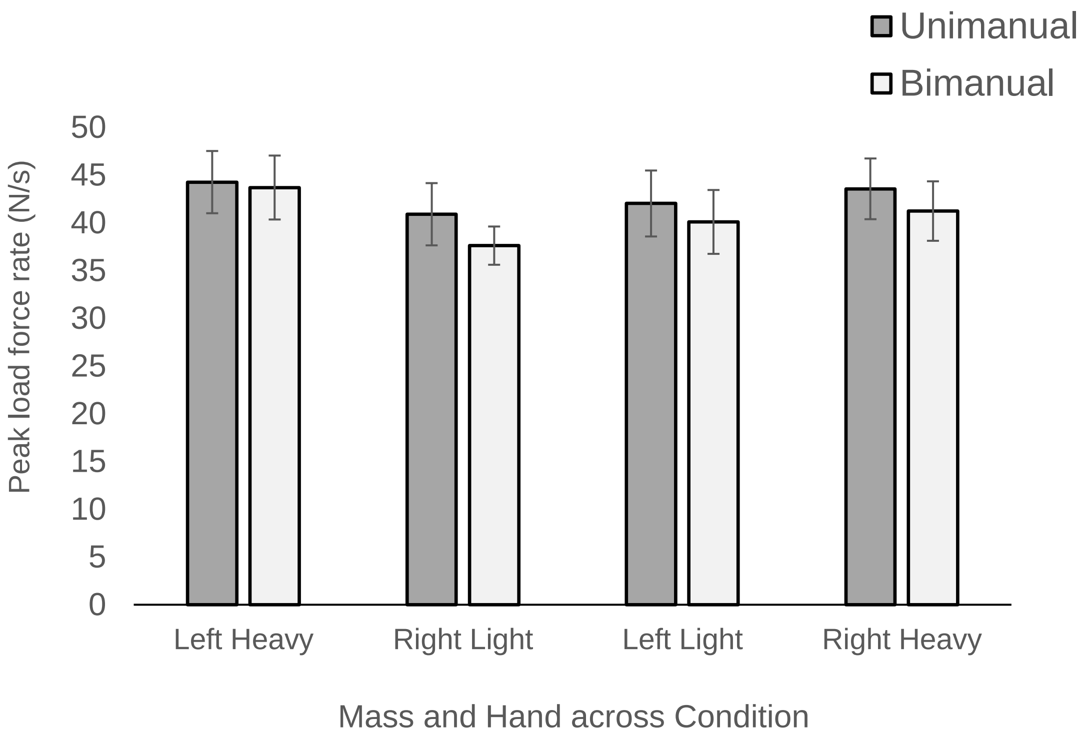

Figure 8. The means of peak LFR values for each hand across conditions

Comparing the LF onset differences between object configurations against zero in the bimanual conditions, the light object was lifted before the heavy object, such that in the Light-Heavy object configuration the left hand lifted earlier than the right hand (M = -43.51 ms, SD = 48.87; $t(20) = -4.08$, $p < .001$; Figure 9) and the Heavy-Light object configuration the right hand lifted earlier than the left hand (M = 32.57 ms, SD = 52.14; $t(20) = 2.86$, $p = .01$).

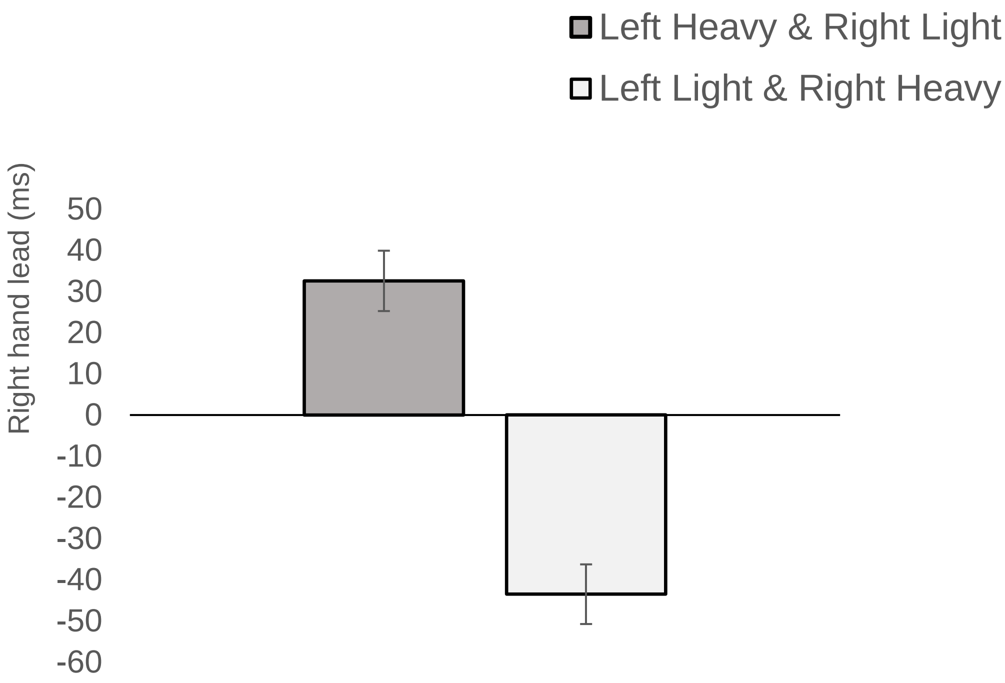

Figure 9. The mean difference between right and left hand LF onset (which one started lifting upwards first), in both mass configurations. Positive values reflect an earlier right hand LF onset while negative values an earlier left hand onset. The differences were both significant, in the Left Heavy and Right Light configuration, the Right hand was faster, and in the Left Light and Right Heavy, the Left was faster)

Online force control

Participants gripped the heavy object with more force than they used to hold the light one (5.43 N vs. 4.12 N; $F(1, 20) = 84.84$, $p < .001$, $\eta_G^2 = .722$; Figure 10). However, there was no difference between the bimanual and unimanual conditions ($F(1, 20) = 0.12$, $p = .72$, $\eta_G^2 = .002$), nor between Hand ($F(1, 20) = .002$, $p = .96$, $\eta_G^2 < .001$). There were no interactions between Condition and Mass ($F(1, 20) = 0.88$, $p = .36$, $\eta_G^2 = .038$), Condition and Hand ($F(1, 20) = 1.98$, $p = .17$, $\eta_G^2 = .064$), Hand and Mass ($F(1, 20) = 1.04$, $p = .32$, $\eta_G^2 = .041$), or Condition and Hand and Mass ($F(1, 20) = 1.1$, $p = .3$, $\eta_G^2 = .029$).

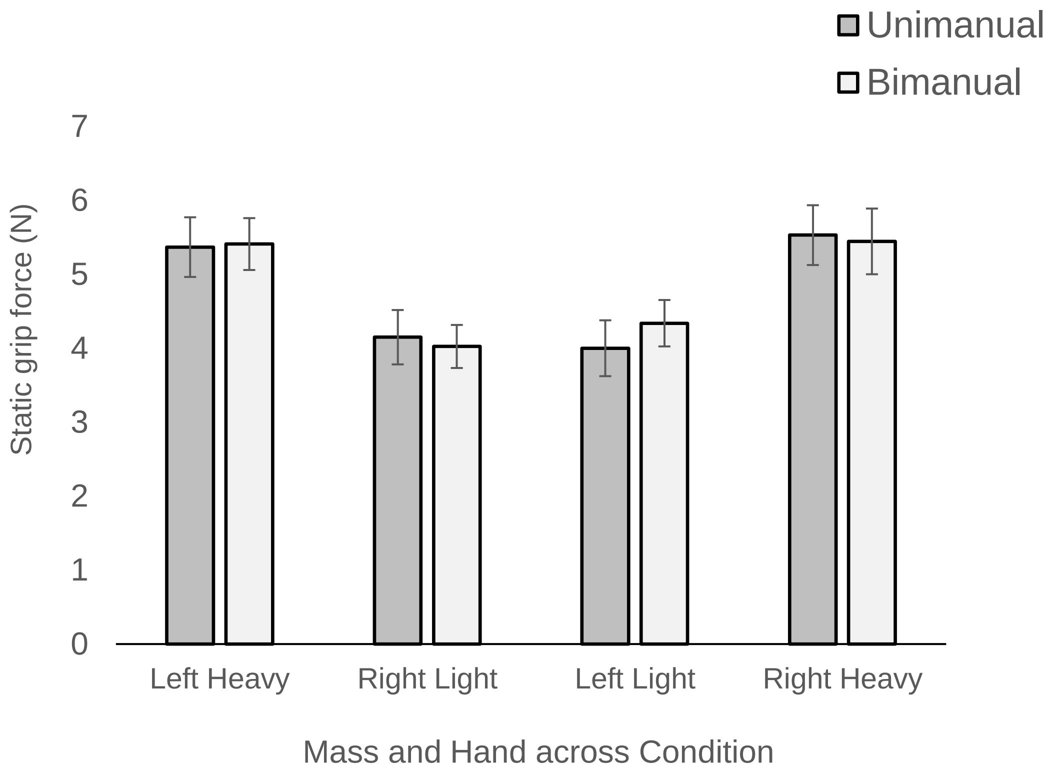

Figure 10. The means of static GF values for each hand across conditions. First two sets of bars reflect one hand/mass configuration and the last two sets the other. Participants always lifted differently weighted stimuli when lifting with both hands

This experiment demonstrated how participants controlled their grip forces when lifting differently-weighted objects with either hand concurrently. There was no evidence of overflow in these contexts – higher forces were used to lift heavier objects regardless of condition, and the effect of object mass did not differ between the bimanual and unimanual lifts. Rates revealed that the right hand was slower in GF scaling, providing support for the notion that the right hand exhibits accuracy traits and the left balance traits (Buckingham et al., 2012; Ross & Roche, 1987). Additionally, the light object was lifted before the heavy one regardless of mass configuration. These results suggest that fingertip forces are parameterised independently for each hand when lifting disparate weights. Participants used grip forces similar to those used when each hand lifted in isolation regardless of the different mass in the other hand. However, that investigation was limited in regard to the situation, in which both hands had already lifted and optimised a stable hold. In such a situation, independent application of static grip force could have been easier to achieve through time.

2.4 Experiment 3: Lifting asynchronously

This experiment was designed to address the aspect of online force control under the same paradigm. That is, whether the online control of static grip force is influenced by the lifting action of the other hand. If there is overflow between hands when there are demands for fingertip force control, there may be static force modulation on the holding hand during the other hand's lifting stage.

2.4.1 Methods

Participants

A total of 24 self-reported right-handed individuals (mean age 22.1 years, SD = 2.4, range from 19-28) were recruited from Heriot-Watt University, Edinburgh, comprising of 10 males and 14 females. Assessment of handedness was performed online as a follow-up with the use of Edinburgh Handedness Questionnaire. All participants had normal or corrected-to-normal vision and no motor impairments. All participants gave informed consent prior to testing, and all procedures were approved by the local ethics board.

Stimuli and procedure

The stimuli and setup were identical to Experiment 2. Participants lifted one object with one hand (precision grip) at the sound of the cue and held the object in a stable manner at a height of 23cm (indicated by a height marker next to the stimuli) for the duration of the trial (seven seconds). Four seconds after the first sound cue, another cue sounded and participants reached and lifted the second object with their other hand at the same height while still holding the first object, and held it in a stable manner for the rest of the trial. Seven seconds after the first cue, the final cue sounded and they returned both objects on the felt pads. Participants were randomly allocated into two groups. The first group lifted the first object (the holding hand's object) with their right hand and lifted the second object (the lifting hand's object) with their left. Participants in the second group used their left hand for holding and their right for lifting. Fatigue effects were minimised with this setup as the length of the experiment was scaled down to 30 minutes; otherwise, if the factor of holding hand configuration was kept within group, the session would last up to an hour. Each participant performed 60 randomised trials, 20 for each mass configuration (20 Left hand - Light mass and Right hand - Heavy mass, 20 Left hand - Heavy mass and Right hand - Light mass, 20 Left hand - Light mass and Right hand - Light mass). In each trial, the holding hand's static grip force was segregated into three temporal epochs, with a crucial state of action captured within each one: Unimanual holding (0.5 a second duration, from second 2.5 to 3), During other hand's lift (from the point where the grip force of the lifting hand exceeded 0.1 Newtons and for 0.5 seconds), and Bimanual holding (0.5 seconds duration, from second 5.5 to 6) (Figure 11). The 0.5 second temporal window was used at all three grip force action epochs, because that was the average lifting duration of the lifting (second) hand.

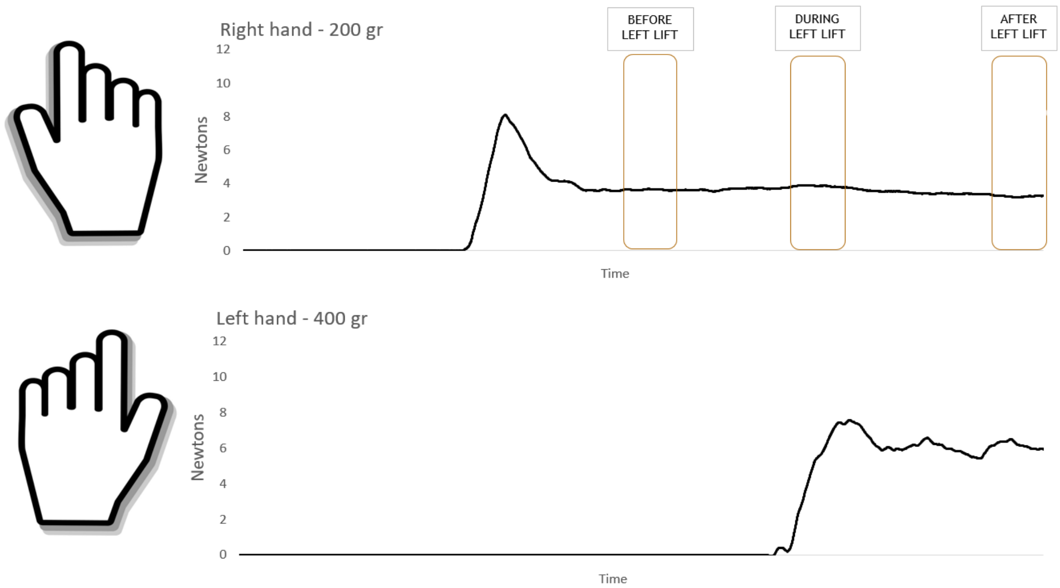

Figure 11. Example trial of the holding hand's grip force profile across time, and how each action epoch was segregated

To directly examine the effect of the lifting hand's mass on the holding hand, static force was examined only in the conditions where the holding hand's mass was constant; Equal (both hands lifted 200 grams), and Lighter (holding hand 200 grams, lifting hand 400 grams). In simpler terms, the level of the Mass factor where the holding hand lifted the heavier, 400 gram object, was removed.

Mean static GF was analysed with a 3×2×2 mixed ANOVAs, with factors of Epoch (Unimanual holding, During other hand's lift, Bimanual holding) and Mass (equal, lighter) as within-group, and Holding hand (Left, Right) as a between-groups factor.

2.4.2 Results & Discussion

Online force control

There was no effect of Mass (F(1, 11) = 1.01, p = .33, η_G^2 = .058) or Holding hand (F(1, 11) = 0.26, p = .61, η_G^2 = .011), but an effect of Epoch was observed (F(1.21, 13.33) = 6, p = .02, η_G^2 = .283; Figure 12). No interaction was found between Epoch and Mass (F(2, 22) = 2.74, p = *.09*, η_G^2 = .183), Epoch and Holding hand (F(2, 22) = 0.2, p = .81, η_G^2 = .021), Holding hand and Mass (F(1, 11) = 0.28, p = .61, η_G^2 = .018), or Epoch and Holding hand and Mass (F(1.23, 13.61) = 1.31, p = .28, η_G^2 = .069).

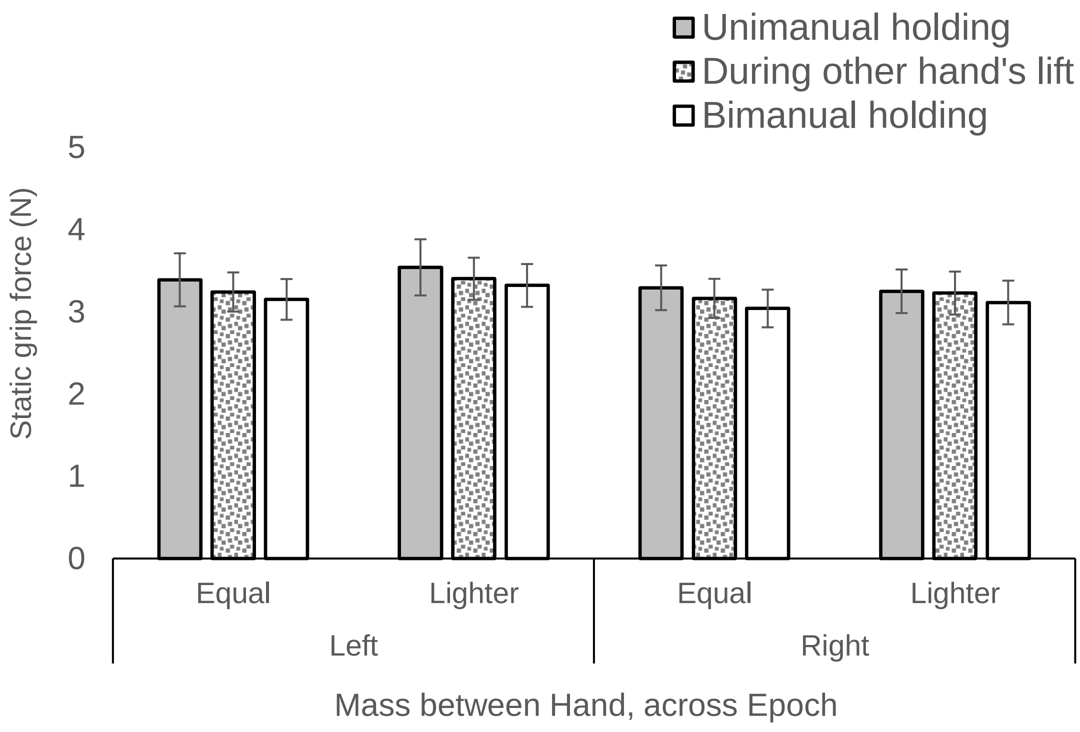

Figure 12. The mean static GF values for each mass configuration. Equal – when holding hand was hefting an object of equal mass to the lifting hand (both 200gr), and Lighter – when lifting hand was lifting a heavier object (400gr) to the holding hand. Left and Right describe the holding hand. Three conditions represent the Unimanual holding (only holding hand), During other hand's lift (the time period when the other hand was lifting), and Bimanual holding (when both hands were holding their respective objects)

This experiment looked for any potential influence of lifting an object of equal or different mass to the other hand's object, while the other hand was already holding a similar object in a stable manner. The mass being lifted by the other hand had no obvious effect on the holding hand's grip force, instead observing a consistent reduction of static grip force as the trial unfolded. That is, holding hand's static grip force was lower during the other hand's lift compared to when it was holding an object in a unimanual context, and was further reduced when both hands were holding their objects in a stable manner. Still, results show no overflow of forces from one hand to the other at any point during lifting or holding an object of either identical or different mass. Specifically, parameters of both sensorimotor prediction and online control appear to operate independently, without overflow effects between hands. However, we can rule out the possibility that this independence may be evident only in situations where both hands are performing the same type of task, i.e. object lifting. This can be achieved by introducing a different type of task to one hand, and examine online force control on the other.

2.5 Experiment 4: Lifting with one hand, tapping or typing with the other

This experiment featured one of the motoric tasks that was shown to cause significant overflow between hands (Peters, 1985). This is a type of cognitively demanding task that is unrelated to lifting, and has the potential to examine whether overflow can have an impact on grip force control. To conclude this series of examinations on the potential overflow of one hand's fingertip forces on the other, a final experiment tested whether performing an ordinary task such as tapping or typing with one hand could influence the static grip force of the other hand that was holding an object. Assuming that the type of task is a key factor in static grip force control, then a degree of force overflow is expected on the holding hand from the other, tapping or typing hand.

2.5.1 Methods

Participants

A total of 20 self-reported right-handed individuals (mean age 22 years, SD = 1.9, range from 19-26) were recruited from Heriot-Watt University, Edinburgh, comprising of 7 males and 13 females. Assessment of handedness was performed online as a follow-up with the use of Edinburgh Handedness Questionnaire. All participants had normal or corrected-to-normal vision and no motor impairments. All participants gave informed consent prior to testing, and all procedures were approved by the local ethics board.

Stimuli and procedure

Similar to Experiment 1, the same 400 gram black cylinder (7.5 cm diameter, 7.5 cm tall) was always placed on the right side of the participant. Force data were recorded at 500Hz. On the left side of the participant, symmetrically opposite to the cylinder, a white round felt marker was placed. A wireless keyboard was placed beside the white mark (Figure 13). The participants went through four counterbalanced blocks of trials, one for each condition. All trials consisted of two distinct sections separated by a sound cue. In the first section, starting with a sound cue, the participant lifted the cylinder with their right hand and held it in a stable manner at a height of 23cm indicated by the height indicator next to the cylinder, and placed their left hand's index finger in a pointing fashion on the white marker. This section lasted for three seconds, and was the same for all participants and all conditions. On the 3^{rd} second, another cue sounded and the second section began. That section depended on the condition that was pre-instructed before the start of each block, and it always lasted for four additional seconds (7 seconds total per trial). On the Control condition, participants were instructed to remain as they were at the end of the first section of the trial, holding the object with their right hand and keeping their left hand's index finger on the white marker. On the Rhythmic Tapping condition, a metronome click played for four seconds (90bpm) and they were instructed to tap with their left hand's index finger on the white marker, matching the tempo. On the Rapid Tapping condition, they were instructed to tap "as fast as possible" with their left hand's index on the white marker (no metronome). The last condition was Typing, and they were instructed to type with their left hand the word "saw" once on the keyboard and return to the white marker. The static grip force windows selected for comparison were of half a second duration (500ms) each. Specifically, averaged static grip force of seconds 2.5 to 3^{rd} second (when right hand's object was stable and left hand idle) and seconds 5.5 to 6^{th} (midpoint of the left hand's task execution), "unimanual holding" and "during other hand's task" respectively.

The mean static grip force of the holding hand was analysed with a 2×4 repeated-measures ANOVA with factors of Epoch (Unimanual holding, During other hand's task) and Condition (Control, Rapid Tapping, Rhythmic Tapping, Typing).

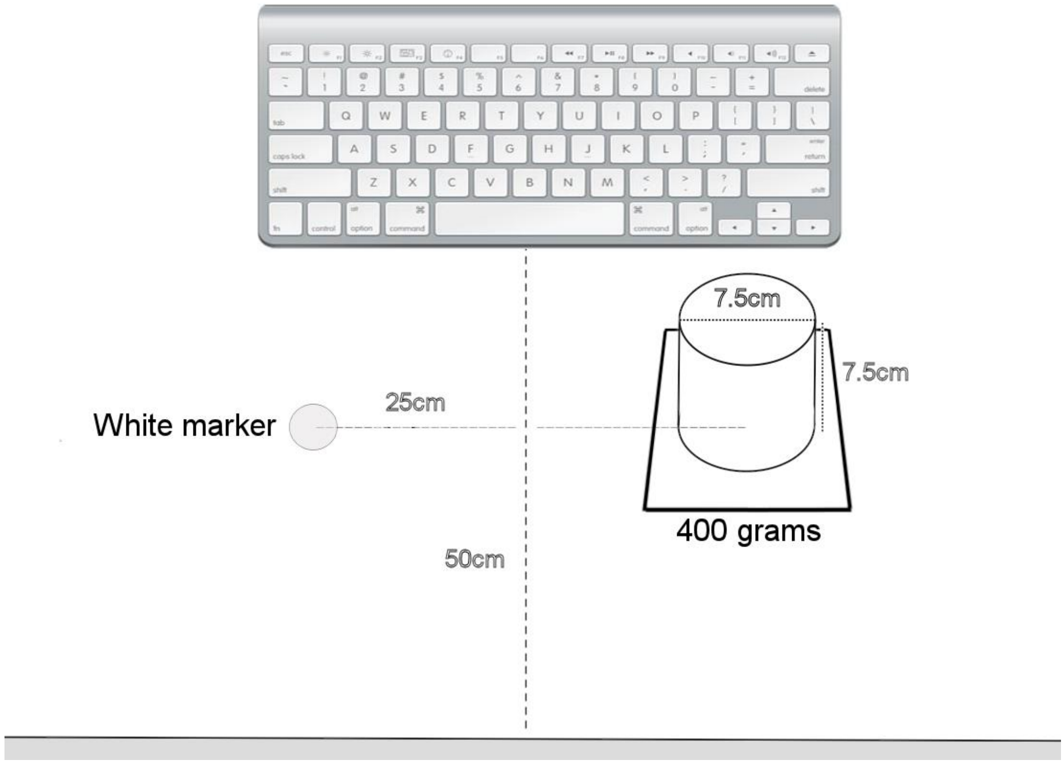

Figure 13. Schematic of the experimental setup of the table surface from the participant's perspective

2.5.2 Results & Discussion

Online force control

There was a significant effect of Condition (F(3, 57) = 5.43, p = .004, η_G^2 = .162; Figure 14), but not an effect of Epoch (F(1, 19) = 0.54, p = .47, η_G^2 = .021). Pairwise comparisons showed that participants held the object with more force during the Rapid Tapping condition than during Control (M = 6.17 N vs. 5.38 N; p < .001) and more force during Rhythmic Tapping than they did during Control (M = 6.12 N vs. 5.38 N; p = .02). Control did not differ from Typing (p = .89), Rapid Tapping did not differ from Rhythmic Tapping (p = 1) nor from Typing (p = .84), and neither did Rhythmic Tapping from Typing (p = 1). However, there was no significant interaction between Condition and Epoch (F(3, 57) = 0.24, p = .87, η_G^2 = .006).

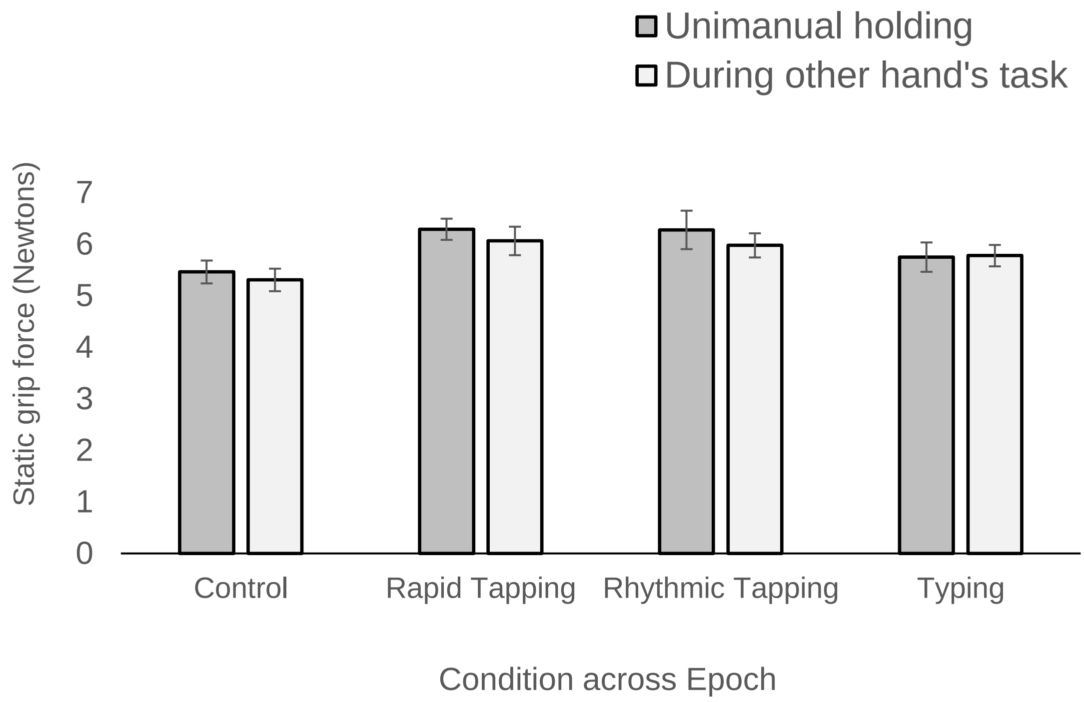

Figure 14. The mean static GF values for each Epoch within every Condition

This experiment tested if an otherwise stable holding hand can be influenced by the other hand performing an ordinary task, however one that is known to be prone to overflow between hands (Peters, 1985). When its counterpart was performing a tapping task, the holding hand held with more force than when the other hand was resting. However, as these differences were also observed in the holding hand before the other hand initiated its task, this excess force is unlikely to be a consequence of the task itself. Indeed, the lack of interaction between Epoch and Condition indicates that the effect of condition is not due to the performance of the other hand, but instead a consequence of task set (i.e., instruction and/or task anticipation).

2.6 Chapter 2 discussion

This series of experiments aimed to investigate how actions undertaken by the other hand could influence fingertip forces when lifting and holding an object, both in the planning and the online control phase. Experiment 1 explored whether lifting two identical objects bimanually would differ from when lifting these objects with one hand in isolation. Lifting with one hand or both hands had no impact on the task in terms of sensorimotor prediction, with equivalent levels of peak grip force rate prior to liftoff.

However, both hands applied additional static force in the bimanual condition compared to the unimanual condition. This increase of ~0.3N might reflect a bimanual cost in static force – to our knowledge the first description of such an effect. Next, to examine if there was any evidence of overflow between the hands, simultaneous lifts of objects with different masses were compared to unimanual equivalents. Results suggested that when there was a different mass in each hand, sensorimotor prediction was still unaffected in a bimanual context; unimanual grip force rate and static force did not differ from bimanual grip force rate and static force. It is important to mention that the lack of a bimanual cost in Experiment 2, in contrast to Experiment 1, was surprising and unexpected. This finding is not consistent with the reach-to-point literature where asymmetrical movements introduce an increased bimanual cost (Blinch, Franks, Carpenter, & Chua, 2015; Spijkers, Heuer, Kleinsorge, & van der Loo, 1997). To add to this, there was no temporal coupling as expected, but each hand started lifting the lighter object first. Experiment 3 examined how static grip force of one hand was modulated while the other hand started lifting an object. The different masses of the lifting hand's objects did not contribute to any changes in the holding hand's grip force. To conclude this series of studies, Experiment 4 looked if static grip force was influenced when the other hand was performing a range of tapping tasks. Comparing the holding hand's grip force before and during the other hand's tasks, no changes in static force were found. However, static force was significantly increased in the tapping conditions compared to unimanual conditions, regardless of the other hand's involvement in the task.

Overall, this series of experiments suggests that the fingertip forces of each hand are independently scaled for each object of different mass, that is, fingertip forces of one hand were not influenced by those of the other. These results are consistent with how individuals coordinate their grip scaling in reach-to-grasp studies (Jackson et al., 1999; Mason & Bruyn, 2009) on the question of hand yoking. Our findings suggest that there is no apparent yoking of forces between hands in a bimanual context. However, in the Jackson et al. study when participants were reaching to grasp objects bimanually, while independently scaling their aperture to the size of each target object, there was an increase of both peak grip apertures regardless of grasping context – a bimanual cost in terms of grip aperture scaling. In the current experiment, there was a similar bimanual cost of mean static force when holding bimanually, compared to when holding unimanually when objects were of the same mass, but not when their mass differed in Experiment 2. In the latter experiment, fingertip forces were not coupled as each hand's force performance was identical to its unimanual equivalent. Our findings in the first two experiments suggest that the reach-to-grasp system differs from the reach-to-point system in that the model of neural crosstalk does not apply. The model describes the theory that two systems can be linked functionally and controlled by one process to yield the desirable action (Marteniuk et al., 1990). The authors argue that such a functional link can affect the accuracy of each of the two components and offset the result of each to be matched with the other. Here, the distinction is speculated to be, in part, due to accuracy demands and thus speed, of each type of movement, as noted in past studies (Diedrichsen et al., 2004; Mason, 2008; Mason & Bruyn, 2009). The term 'speed' is used in this context to describe processing and motor execution of a motor command rather than an implicit task requirement issued to a participant. Reach-to-point motions are predominantly fast movements with a clear arm flexing action that terminates at the moment of target contact, while a reach-to-grasp execution involves a more complex set of commands that include the grasping component. It is proposed that the distal muscles involved in grasping and lifting behave differently to the proximal muscle groups of the shoulder/arm typically used to reach and point (Dohle, Ostermann, Hefter, & Freund, 2000). In situations where speed is crucial for the successful execution of a task, such as reach-to-point experiments, bimanual coupling may be beneficial due to reduced degrees of freedom in movement parameterization (Temprado et al. 1997). Interacting with objects, as opposed to manual localization tasks, usually involve slower actions due to the tasks demands (grip aperture modulation, coordinating grip and load forces during liftoff, maintenance of forces). Situations where a task requires slower movements serves as a good example of the suggestion posed by Mason and Bruyn (2009) that, in situations where coupling is not beneficial it does not occur, and each hand's action is parameterised separately. The issue of speed may be the case with the collective evidence of the older studies on bimanual coordination using reach-to-point paradigms, and why these asymmetries are not present in the recent reach-to-grasp paradigms; the grip/lift system may behave in a similar fashion as the reach-to-grasp, since both require slower actions.

Similarly, in Experiment 3 there was no increase of holding hand's force when the other hand lifted a heavier object, an observation that suggests no overflow of forces in any part of the lifting phase. It appears that fingertip forces decreasing at each epoch, and that decrease may have been a general tendency to optimize static force as time progressed, regardless of the difference in force demands between hands. In Experiment 4, an increase of force during the various Tapping conditions was expected, but this increase was evident even before the other hand had started tapping, suggesting that the increase was not caused by the action per se. It is speculated that this increase in static force was a consequence of task preparation. It may have been that prior knowledge of the type of task participants would be required to perform with the other hand, primed the sensorimotor system to preconfigure fingertip forces to include an extra safety margin for the holding hand to maintain its grasp successfully.

To sum up, this series of studies has shown that overflow between the fingertip forces of each hand when lifting and holding is not apparent in the same fashion as in broader bimanual coordination tasks requiring rapid reaching movements, such as pointing at two asymmetrical targets bimanually. In the latter scenario, one hand can influence the other in timing (Fowler et al., 1991) and direction (Diedrichsen et al., 2004). It seems to be a phenomenon exclusive to fingertip forces, as even more complex motor tasks are not capable of introducing significant overflow from one hand's forces to the other's. In contrast to manual localisation literature, fingertip force scaling seemed to operate independently; individuals are able to lift objects with both hands just as successfully as they can lift one object with one hand. There was a degree of force overcompensation when both hands were required to apply identical forces, which could be interpreted as a bimanual cost in this simple situation, a phenomenon not seen when required forces differed between the hands. Similarly, fingertip forces when holding an object were not affected by overflow from the other hand's actions whether those were related or unrelated to object lifting. It appears that both hands operate independently from one another in terms of fingertip force control and parameterization, but show compensatory mechanisms under certain conditions. Most interesting is that those conditions seem to be working in the opposite direction than reaching-to-points tasks. Bimanual cost increases as asymmetries between hands increase when reaching-to-points, and is abolished when asymmetries are introduced in object lifting.

However, these findings also tell us that planning behaves similarly with online control. There were no asymmetries observed in either set of variables, yet sensorimotor prediction appeared to be the more impervious of the two, as there was bimanual coupling evident on the control of forces.

Finding out if this independence is extended beyond the use of the other hand is the aim of the next chapter. While interhemispheric independence between the two symmetrical motor areas involved in hand coordination may be beneficial for tasks involving both hands, input from different sensory domains still have the capacity, as outlined in research below, to influence the way we grip.

3. **Chapter 3:** How does language, sound, and vision affect fingertip force scaling?

3.1 Introduction

Language and manual motoric actions are two domains that have recently received attention as they are found to exhibit interactive properties (Berent et al., 2015; Gagné & Cohen, 2015; Tremblay, Deschamps, & Gracco, 2016). While still under debate, some articles suggest that spoken language was created as a manifestation of motor movements, commonly known as gestures, that were used for communication (Christiansen & Kirby, 2003; Fischer & Zwaan, 2008). The brain activity that mirror neurons reflect when we are observing a manual action, is similar to the brain activity when we are encoding observed gestures, a finding that proposes a close link between how manual actions and how communicative gestures are represented internally (Rizzolatti & Arbib, 1998). Substantial evidence that supports this broad link between the sensorimotor system and language comes from developmental and clinical studies which report strong co-morbidity of language and motor impairments in individuals with developmental disorders, prevalently in the autistic spectrum (Hill, 2001; Jongmans, Smits-Engelsman, & Schoemaker, 2003; Webster et al., 2006; Webster, Majnemer, Platt, & Shevell, 2005). Within a review of specific language impairments (SLI), it became clear to the author that SLI are not specific to language at all, but rather encompass a broad range of impaired systems, including motor coordination (Hill, 2001).

The association between language and motor functions is inevitable, as producing sounds and speech is fundamentally a motor process that involves shaping the orofacial cavity in a particular way to accommodate particular sounds that constitute language (Guenther, 1994). Given this link, it is crucial to understand which facets of the motor system are strongly linked with language. At a cortical level, when we perceive language being spoken, the hand area of the motor cortex is activated (Flöel, Ellger, Breitenstein, & Knecht, 2003). The authors of that study measured cortico-spinal excitation as their main variable of interest with transcranial magnetic stimulation (TMS) to examine if particular components of language could activate the hand motor system. Their findings showed that the hand area was activated during the perception of language, and not by auditory processing or visuospatial processing. Put simply, neither audio nor the viewing alone were enough to cause an activation, but as the authors put it, “pure linguistic perception" was the ideal situation for an activation to occur. Behaviourally, different orofacial cavity configurations, such as placing the tongue at the velum to form a "ke" or protruding the lips to form a "pu" sound, show different RTs when responding with a power grip or a precision grip on a button (Vainio, Schulman, Tiippana, & Vainio, 2013). In simple terms, motor coordination of grasping is affected by motoric processes specialised in producing speech. Moving from phonemes into the realm of meaningful words, research reported that action-related words in particular, exhibit their own somatotopic representation on the human premotor and motor cortex (Hauk, Johnsrude, & Pulvermüller, 2004), differentiating from non-action related words. Looking into how the CNS deals with word context, a study demonstrated that listening to action-related sentences modulates the activity of the motor system (Buccino et al., 2005). This was shown through the use of TMS on participants who listened to foot or hand related sentences, and used their hand or foot to respond accordingly. The use of TMS allowed the authors to record motor evoked potentials (MEPs) during hand or foot sentences and found that hand related sentences modulated MEPs on the hands and vice versa for foot related sentences. The findings were used to conclude that each of these two motor areas is bound by specific language that refers to its functions.

Given those findings, it is important to examine the ways that our motor system is affected by the comprehension of action-related words or sentences, because this would mean that context is more important than the effect of arbitrary auditory input. If the activity of the hand-area on the motor cortex increases during the comprehension of action-related words, and an increase in gripping strength also correlates with increased activity in the same area (Cramer et al., 2002), overflow could be possible. Overflow in this cross-domain context is defined as the phenomenon of a sensorimotor domain's influence on another; in this context, information from the auditory-language domain may affect the processing of motor commands from the sensorimotor domain. It would not be an unreasonable inference, as a recent study demonstrated how spoken language and arm gestures are controlled by the same motor control system (Gentilucci & Volta, 2008). Another study tested whether participants would modulate their constant applied grip force on an object while they were listening to action-related words (Frak et al., 2010). They were instructed to lift a small cylinder to a short height above the surface of a table and hold it while they were listening to words through headphones, while a force sensor attached on the cylinder was recording force variables. The words were nouns and action-related verbs, and the participants took part in two blocks. They were asked to count the number of times they heard a particular word that would be repeated; in the first block a noun and in the second, an action-related verb. Comparing grip forces between the two blocks, on only the target words, the target action-related verb's grip force was significantly higher than the grip force of the target noun's. They found no other differences between non-target words, suggesting that when the participants pay close attention to an action-related verb, there is a degree of overflow to the motor system. Most importantly, this overflow is strong enough to be manifested in measurable grip force changes. Their findings were consistent with the aforementioned studies that linked language with the motor system. A subsequent study involving some of the same authors used sentences, featuring action verbs in both a positive and negative context, simply by negating the action (e.g. "Before the church, Lilian did not shake hands of the future husband"), and a control condition with non-action related verbs (Aravena et al., 2012). Their results suggested that for grip force to be modulated, the context needs to be positive, as they found no differences in the negative condition when compared with the control one, but a significantly increased grip force during the positive action sentence. However, the study was designed to elicit strong mental imagery by using only third-person sentences. Using first-person sentences has demonstrated that it induces a confounding first-person representation of the action, while third-person sentences induce visual imagery separate from a first-person perspective (Jeannerod, 1995; Ruby & Decety, 2001). Their findings, while showing an effect in action related third-person sentences, do not inform whether this effect is due to mentally viewing an action from a third-person perspective or if the context of the word alone can show the same effect. It is possible that viewing any action through visual imagery shows an effect on grip force and if this is true then it still remains unanswered if the comprehension of associated language, without a clear sentence to elicit visual imagery, shows an effect as well.

It is important to understand if this effect is limited solely to language comprehension, or if language production could also show an effect in a similar direction. Participants shouting words such as "Grasp" or "Put Down" while reaching to grasp an object was shown to modulate the velocity profiles of several kinematic measures (Fargier, Ménoret, Boulenger, Nazir, & Paulignan, 2012). It is, so far, unknown if articulating similar words while holding an object can affect an otherwise consistent application of grip force, in a general setting. While it is understood that when maintaining attention a small increase in static grip force is observed (Frak et al., 2010), it is crucial to apply this design without target words being counted. Doing so can inform us whether in various settings such as in surgery, speaking action related words could affect a surgeon's steady force application, regardless of its magnitude.

For the purposes of this series of experiments, I start with the premise that if the motor system is strongly linked with language as the bulk of research suggests, there is a possibility that auditory input may belong somewhere within this link as well. It has been shown that while we open our grip aperture to the proportions of the visually available object, semantic context plays a major role in the formation of the aperture (Glover, Rosenbaum, Graham, & Dixon, 2004). The authors attached labels on wooden blocks that contained semantic word such as “apple” or “grape”. Initial grip aperture was shaped proportionately to the size of the described object in the label, rather than to the wooden block, and to the wooden block’s proportions when labels were absent. However, when the hand was near the target the effect was abolished and aperture assumed the proportions of the wooden block. They suggest the existence of a corrective system that takes action when we are about to physically grasp an object. It appears that the motor system can be primed by words that hold an internal representation, but the effect is overridden by proximity, hinting that the visual characteristics of the physical object become more salient than the earlier contextual representation alone.

It is important to see whether lexical meaningful cues can be generalised to the domain of sound. In a relevant study, wooden balls of different size and mass were dropped onto baked clay plates of various diameters, and participants were successfully reporting the dropped objects to be larger when the plates were larger, only by being exposed to their impact sounds (Grassi, 2005). The masses of the balls were rather light (ranging from 0.35 to 44.5 grams), hence all the sound produced that could inform the participant of their relative mass came from the plate itself. The findings suggest that we are able to perceptually attribute a noisier impact sound to an object being larger than a less noisy impact sound. Moving from perception and to how it can inform prediction, in another study, a small or a large object were placed in front of participants causing either an impact sound or not, under visual feedback or without (Sedda, Monaco, Bottini, & Goodale, 2011). Thus, by measuring kinematics, the authors were able to understand the saliency of sound over vision or vice versa. The relevant measure in their study was their PGA when reaching for the object, and indeed, grip aperture was unaffected and unchanged between small and large objects when vision and sound were absent. When the objects caused an impact sound, regardless of visual feedback, participants scaled their PGA according to the size of the object, and as inferred through the sound of impact. The authors conclude that sound can inform us of size, and appears to affect sensorimotor prediction in the same direction as well. A direct test on whether fingertip forces themselves are also affected was warranted.

Reaching and lifting a novel object, while with seemingly successful coordination and result, is also a process whose success may lie in having observed another person lift that object first. This phenomenon is termed action observation and was first reported in 1992, by monitoring specific single neurons in the monkey's premotor cortex (Pellegrino et al., 1992) which only fired when watching another monkey perform a manual action and when the monkey performed the same action itself. The Broca's area along with a part of the human premotor cortex also activates when we observe action, as both positron emission tomography (Rizzolatti et al., 1996) and functional magnetic resonance imaging (Binkofski et al., 1999) studies reported. Some authors suggest that this system may be crucial for mimicking actions, as well as processing them to gain a deeper understanding of the action themselves (Jeannerod, 1994; Rizzolatti et al., 1996; Giacomo Rizzolatti & Craighero, 2004).

Specifically, this behaviour is thought to arise from a set of neurons coined mirror neurons, that seem to fire similarly when we execute a manual action and when we observe another person perform the same action (Gallese & Goldman, 1998). The bulk of related studies originate from the discovery of a specific set of neurons in the Macaque monkey cortex (Gallese, Fadiga, Fogassi, & Rizzolatti, 1996), and it was not specific to vision. The same set of neurons fire when the Macaque performs an action and when the sound of that action is being heard (Kohler et al., 2002).

Lately, the common method of measuring action observation parameters is by attaching electrodes on the skin over certain groups of muscles, and using transcranial magnetic stimulation (TMS) onto certain motor areas of the human brain. This elicited stimulation is converted into electrical potential in the cortex and travels through the motor system, and being recorded by the electrodes on muscle groups. The resulting potentials recorded have varying values that reflect whether those motor evoked potentials (MEPs) were activated or not during a particular time; usually, an experimental manipulation. The resulting measurement, is ultimately a measurement of cortico-spinal excitation that is showing us at which point during an experiment the relevant muscle groups received excitatory potentials. The authors of a study asked whether low level motor areas, those more relevant to the execution of actions, could be mimicking the observed action as the primary motor areas seem to in terms of brain activity (Baldissera, Cavallari, Craighero, & Fadiga, 2001). The authors elicited the H-reflex on participants while they were observing a video of a hand extending a rubber band wrapped around the index and thumb by increasing grip aperture, and a video of a hand closing its grasp around a sphere, and in their second experiment, watching a hand reach, grasp and lift an object. Indeed, the reaction of the reflex size increased when the hand was opening, decreased when it was closing, and reverted when observing an object being lifted. This study demonstrated that action observation can elicit a more complex effect than solely a mental simulation of an action, but may actually activate muscles themselves. Not limited to visual action representations, but also to auditory action representations, a study demonstrated that multimodal, visual and auditory, stimuli presented simultaneously showed increased selective responses over unimodal or incongruent stimuli (Alaerts, Swinnen, & Wenderoth, 2009a). This suggestion hints that observing action encompasses auditory representations of action in humans, as it does for Macaques (Kohler et al., 2002). Action observation may explain in part why listening to action-related verbs and sentences while holding an object causes the holder to apply additional force while paying close attention to such words and sentences (Frak et al., 2010).

In so far, low level motor processes seem to be affected by action observation, as well as MEPs on flexor muscles of the hand responsible for grasping functions (Baldissera et al., 2001). There is some evidence that shows finger abduction force to be briefly increased after action observation (Porro, Facchin, Fusi, Dri, & Fadiga, 2007). Participants who abducted their index and middle finger repeatedly (trained) showed increased abduction force, similar to the participants who only observed a finger abduction and performed it themselves afterwards briefly (untrained). The control group that did not perform abductions beforehand (untrained) or observed any, did not show any increases as the task progressed. However, more research is needed to understand if object lifting can be ultimately affected by action observation. Little is known on how this effect operates; if it is possible due to the observation of arm and hand/finger features such as muscle contractions, or if is it due to the kinematic properties such as the velocity of the hand's movement. One study, using TMS on M1 motor area to record cortical activation during action observation, suggests that kinematic properties of the actor's arm and hand are the preferable cues that inform the observer of the action and its parameters, such as mass and difficulties that can be present in lifting that particular object (Alaerts, Swinnen, & Wenderoth, 2009b). The same authors conducted a follow-up study to expand their question, and asked which kinematic property in particular is the most critical one (Alaerts, Swinnen, & Wenderoth, 2010). They reported that when only kinematic cues are available or only hand's contraction state cues are available, M1 observation-induced activity correlates with the force exerted on the objects; each cue alone is as informative as the next. However, between muscle contraction states and kinematic cues, their results suggest a strong preference for kinematic cues when both are available and some of the authors argue in a subsequent study that these cues and their respective M1 observation-induced activity are crucial for our estimation of the appropriate level of force we will need to use on a particular object (Alaerts et al., 2010). Put simply, this activity may be reflecting the creation of force predictions.

A follow-up study featuring some of the same authors investigated the temporal parameters of this M1 observation-induced activity, specifically aiming to find at which time point from observation to execution is it happening (Alaerts, de Beukelaar, Swinnen, & Wenderoth, 2011). Their results showed a gradual increase of M1 observation-induced activity as the phases progressed from reach, to grasp, to lift, with the peak of the activity taking place at a late lifting phase. It was important to note that observation-related activity began at the reaching phase, where no haptic information was present, speculating that this activity may be an early processing of prior knowledge of the object's weight and aids in forming force predictions.

If force prediction works in this way, it is important to know of its robustness in terms of multi-modal competition. Specifically, to see how lexical cues affect perceived kinematics when observing others lift the same object, featuring labels that cue to different weights. A study was conducted with this exact question, examining the robustness of force prediction, and discovered that when only textual cues were the only information available, by obscuring kinematic cues, MEPs were similar to situations where kinematic cues were available (Senot et al., 2011). However, the presence of labels did not affect MEPs when both types of cues were available, observed through trials where the weights of the objects and the labels (light vs heavy) were incongruent. Again, kinematic cues seem to be the most powerful and informative predictor of force requirements. The phenomenon is persistent even in situations where the object is familiar (Uçar & Wenderoth, 2012). In such situations, bottom up kinematic information is still more salient to the motor system forming force requirements, than prior familiarity of the object's weight representations.

But what happens when that bottom-up visual information of material and size tells us that all the objects are the same, but in reality, some have different masses? Will kinematics of the lifter show that a heavier one has been lifted? Indeed, participants interacted with identically looking objects in a series of lifts, and experienced some unexpected perturbations of mass in some trials (Reichelt, Ash, Baugh, Johansson, & Flanagan, 2013). The perturbation trials in this 'solo' block were used as a baseline, compared against those of a 'coupled' block, where an actor lifted the same objects first, and against those of an 'informed solo' block, in which participants were informed of a mass change before it happened. The participants performed as expected for an over- or under- estimation of weight, lifting with a faster rate when they expected a heavier object and vice versa. The findings of this study clearly suggest that sensorimotor prediction is affected by action observation, specifically in the planning phase; observed kinematics are used by the observer to update their estimations of weight on that object.

However, the findings of that study involved the observer's, but not the actor's parameters. Will the actor's knowledge or ignorance of the object's changing weight, affect their kinematics, and subsequently the observer's sensorimotor performance? Kinematic information seems to also convey another important message; how not to act on an object. We learn how to successfully lift an object through observation, much more efficiently when we see errors being made during lifting than seeing successful, intact, expert lifts (Buckingham et al., 2014). Comparing how participants lifted an object after having watched expert lifts with those having watched novice, error-prone lifts, the authors of that study found the latter to have performed fewer errors than those who watched expert lifts. Identically weighted cubes of different sizes were used and caused over and underestimation errors, of which the former were the ones significantly reduced for the observers of novice lifts. The findings suggest that errors in lifting are more informative to the observer regarding the true mass of an object, than expert lifts are Additionally, MEPs were measured in a group that only viewed the videos. Modulation of cortico-spinal excitability was evident only when participants were watching expert lifts and not novice ones. As such, this chapter features expert lifts, capable of eliciting cortico-spinal excitation, and investigates if action observation can have a measurable impact on fingertip forces.

Beginning with the auditory domain, it is first asked if the sound of an object being dropped on a surface is sufficient to cause us to scale our fingertip forces appropriately to the quality of the impact's volume, as a heavier object causes different sound properties than a lighter one. Additionally, whether dropping the same object from a higher point, thus causing a louder sound, can lead our sensorimotor system to perceive it as heavier and scale its fingertip force application accordingly. The findings can potentially show whether fingertip force scaling will behave similarly to grip aperture, that is, if grip force peaks will reflect the perceived mass of the object rather than the physical one.

3.2 Experiment 1: Predicting mass with object dropping sounds

3.2.1 Methods

Participants

A total of 20 self-reported right-handed individuals (14 females, mean age 19.3 years, SD = 1.7) were recruited from Heriot-Watt University, Edinburgh. Assessment of handedness was performed online as a follow-up with the use of Edinburgh Handedness Questionnaire (three were unreachable). All participants had normal or corrected-to-normal vision and no motor impairments. All participants gave informed consent prior to testing, and all procedures were approved by the local ethics board.

Stimuli and procedure

A custom-written script in MATLAB (Mathworks) controlled the trial start and end cues with a short "beep", and handled the data collection from a pair of force sensors (Nano17, ATI Tech). PLATO goggles were used to block the participants' vision when needed. The stimuli were four wooden boxes of identical size. However, two weighed 369 grams (Light) and the other two 518 grams (Heavy). One force sensor was mounted on top of one of the Light stimuli and the other on top of one of the Heavy ones, with a custom-made handle. The Light and Heavy objects without the force sensors attached were used by the experimenter (dummy boxes) to create the sound by dropping them, and were never seen by the participants. The participants were only exposed to either the Light or the Heavy box with a force sensor attached. A cardboard box was used as a height indicator, aiding the experimenter in dropping each box from a height of either three or six cm from the table surface.

Participants sat on a chair in front of a large table and placed their hands on a starting button, located 25 cm away from the edge of the table, in a relaxed manner (Figure 15a). PLATO goggles were opaque for that stage. The relevant stimulus (Light or Heavy) was placed 35 cm away from the participant (edge of the table). The experimenter lifted and released the dummy box, with the matching mass to the participant's stimulus, from either three or six cm height. The experimenter's lifting and dropping area was located approximately 60cm away from the participant. After the dummy box created the impact sound, the experimenter hid the dummy box, the short "beep" sounded, PLATO goggles cleared, and participants reached with their dominant hand. They lifted the object in front of them (either Light or Heavy), and placed it back at the second "beep" indicating the end of the trial. The duration of each trial, from goggles clearing to the last "beep" was five seconds and data were recorded at 1000 Hz. Each session featured a total of 80 randomised trials (20 for each level of Height and Mass) and lasted approximately 40 minutes.

Peak GFR and peak LFR were analysed, each with a 2×2 repeated-measures ANOVA with factors of Height (High, Low) and Mass (Heavy, Light).

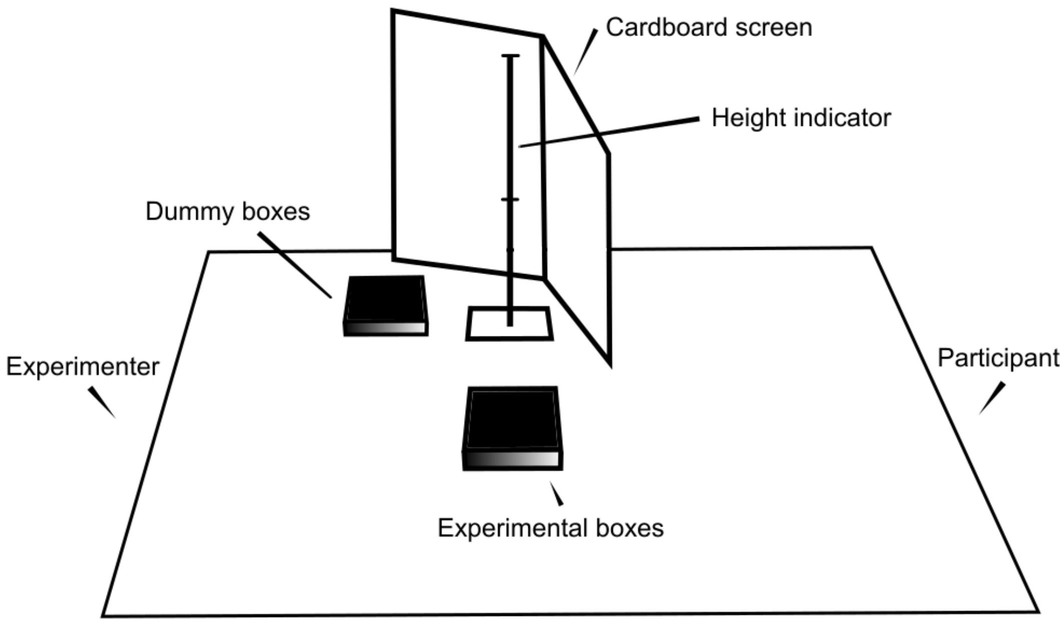

Figure 15a. Schematic of the experimental setup of the table surface from the participant's perspective

3.2.2 Results & Discussion

Sensorimotor prediction

GFR analysis yielded a significant effect of Mass (F(1, 19) = 5.17, p = .03, η_G^2 = .158) but no main effect of Height (F(1, 19) = 2.21, p = .15, η_G^2 = .084), and no interaction between Mass and Height (F(1, 19) = 0.88, p = .36, η_G^2 = .026; Figure 15b).

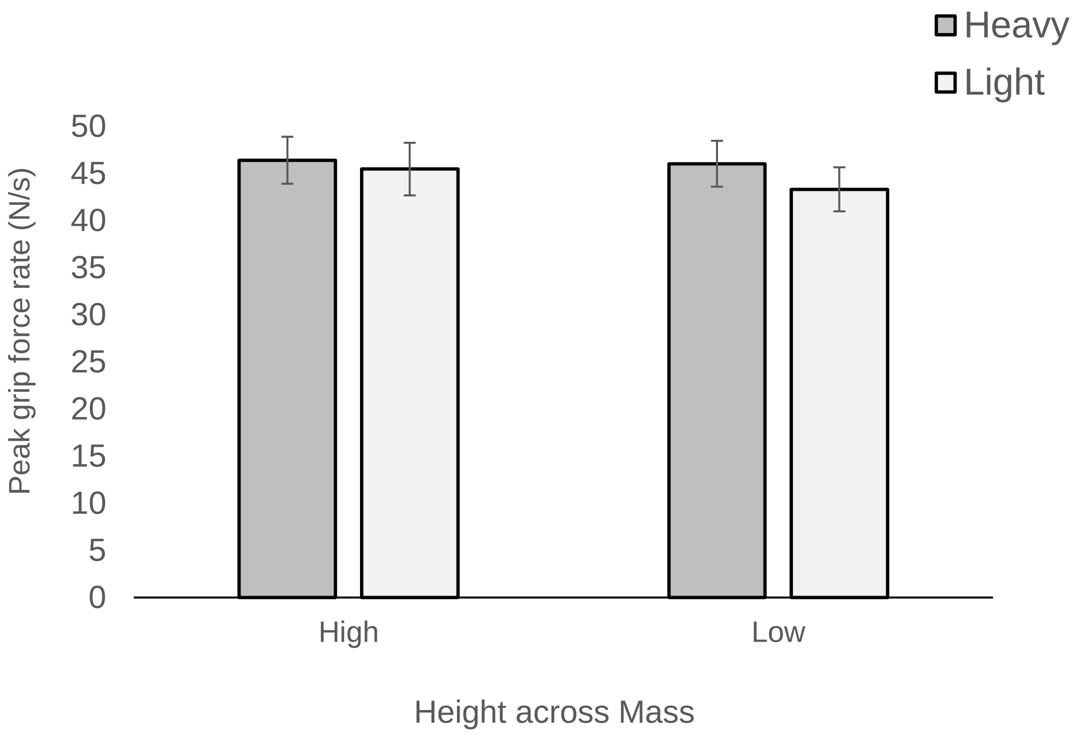

Figure 15b. The means of peak GFR values for each mass across heights

Regarding LFR, there was no main effect of Mass (F(1, 19) = 0.75, p = .39, η_G^2 = .024) but a significant main effect of Height (F(1, 19) = 6.05, p = .02, η_G^2 = .203). No interaction between Mass and Height (F(1, 19) = 2.01, p = .17, η_G^2 = .076; Figure 16) was found.

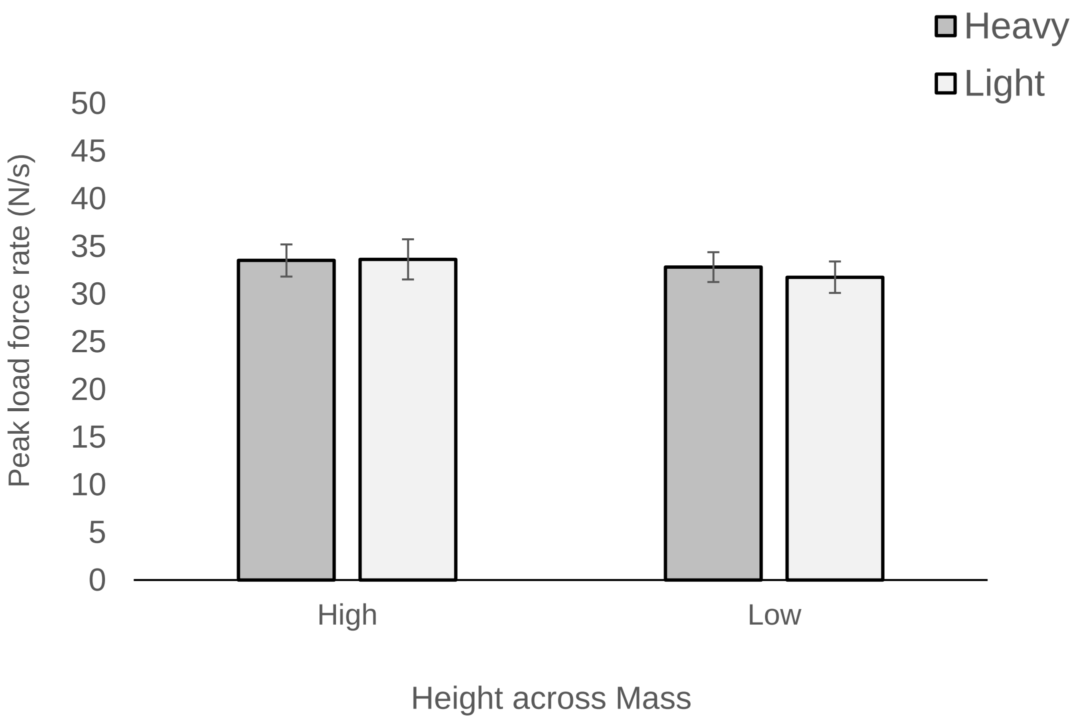

Figure 16. The means of peak LFR values for each mass across heights

Grip force rates corresponded to the change of the respective object's mass; heavier objects called for higher grip force rates. The main effect of load force rate however was interesting, as it reflected the speed of lifting vertically. Objects dropped from the higher point caused the participants to lift faster than the objects dropped from the lower point. Interpreting the findings, it appears that a louder impact sound can affect our motor execution in a specific way; that is, we lift faster with our whole arms, possibly because we perceive the louder noise to belong to a heavier object. This interpretation fits well with what was observed in Chapter 2, by taking into account the reach-to-point literature; when whole arm movements are involved, parameters differ from when only fingertip forces are engaged. More importantly, this study showed that impact sounds can prime the motor system to form weight representations in preparation for a lift that can be reflected on actual forces, albeit on those taking place during sensorimotor prediction. The next experiment was designed to test if listening to meaningful words can prime the motor system in a similar manner.

3.3 Experiment 2: Priming fingertip forces with language comprehension

Since meaningful lexical context can prime grip aperture with both size-explicit ("small", "large") (Gentilucci & Gangitano, 1998) and size-implicit ("apple", "grape") (Glover et al., 2004) visual cues, manual-related auditory cues were explored in the next experiment. The words were weight-related (e.g. "heavy", "dense"), lifting-related (e.g. "elevate", "grasped"), and control nouns. It is hypothesised that listening to those context-related words can prime fingertip force scaling before lifting an object which could be potentially observed in increased peak grip forces when initially lifting.

3.3.1 Methods

Participants

A total of 25 self-reported right-handed individuals (mean age 22 years, SD = 2.2, range from 20-31) were recruited from Heriot-Watt University, Edinburgh, comprising of 14 males and 11 females. Assessment of handedness was performed online as a follow-up with the use of Edinburgh Handedness Questionnaire. All participants had normal or corrected-to-normal vision and no motor impairments. Due to technical errors during data collection code execution, three participants were removed from the analysis, and another was removed as the majority of the scores were, on average, three standard deviations over the mean. All participants gave informed consent prior to testing, and all procedures were approved by the local ethics board.

Stimuli and procedure

The force sensor was attached to a 413 gram black cube (7.5 cm) and measured forces at 200Hz processed with a low-pass Butterworth filter, with a cut-off frequency of 14 Hz. A custom-made MATLAB script was used for data collection. Words were articulated by a female, recorded on an Apple iPhone, moved to a MacBook Pro, and played back with Apple iTunes, through Sony stereo headphones (MDR-V300).

Participants sat behind a desk facing the experimenter and had their hands placed on the desk at a resting manner, wearing headphones. The cube was placed at midline in front of them on a green felt pad. When a word was played back, there was a five second interval until a “beep” sounded which indicated the cue to reach out and lifting the cube by the handle in a vertical manner with index and thumb, to shoulder height. A total of 73 lifts were performed by each participant corresponding to 10 words with a weight context (such as “heavy”, “dense”, “large”), 10 words with a lifting context (such as “holding”, “grasped”, “clenched”), and 10 control words (such as “rabbit”, “summer”, “income”) played back twice each for a total of 60 words. The 13 remaining lifts featured the word “Reward” and served as a target word which the participants were asked to count to maintain attention. The data from the target word was not included in the analysis. All participants correctly identified the number of target words. The word stimuli were controlled for number of letters within each condition and the trial order was randomised between participants. The experiment lasted for approximately 20 minutes.

The dependent variables (peak GFR and peak LFR) were analysed with separate one way repeated measures ANOVAs, under three levels of Condition (Control, Lifting, Weight).

3.3.2 Results & Discussion

Sensorimotor prediction

There was no significant effect of condition for GFR ($F(2, 40) = 1.21$, $p = .31$, $\eta_G^2 = .045$; Figure 17) or LFR ($F(2, 40) = 0.06$, $p = .94$, $\eta_G^2 < .001$; Figure 18). The rates of grasping and those of lifting were not primed by the lexical content.

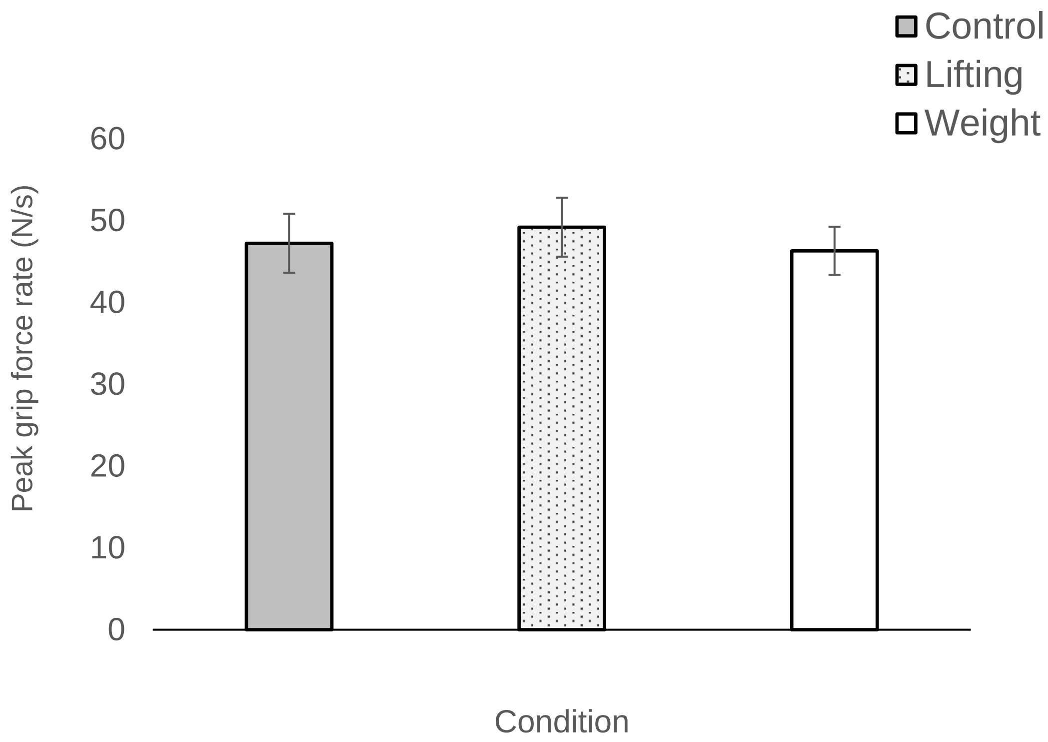

Figure 17. The means of GFR across conditions

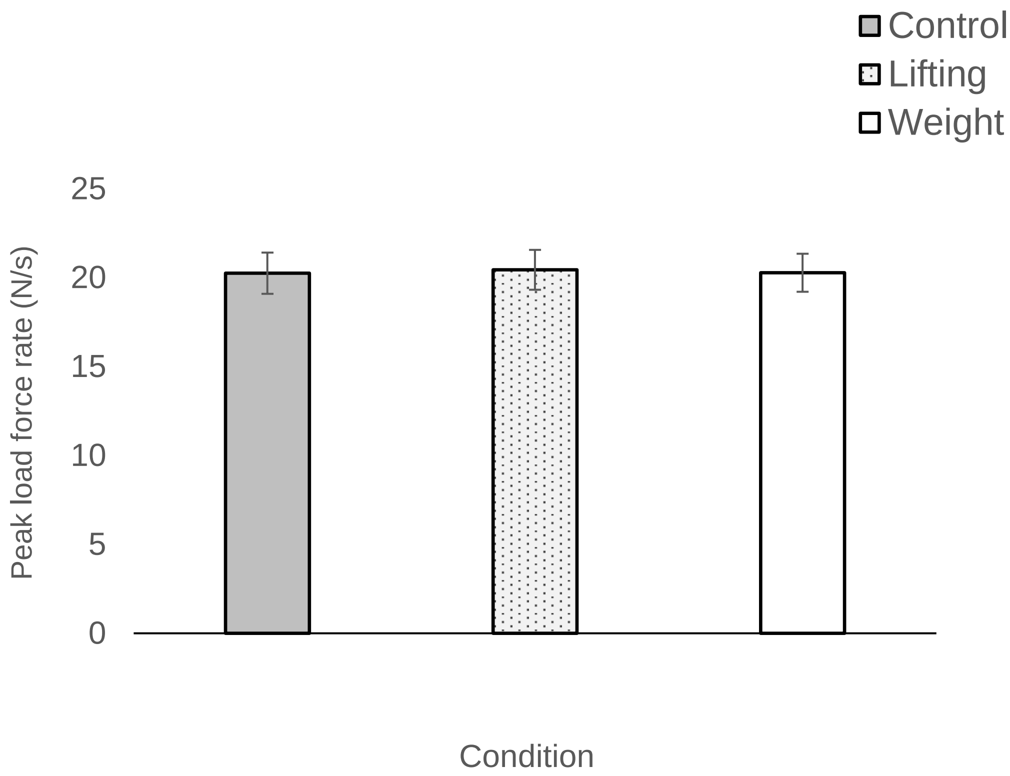

Figure 18. The means of LFR across conditions

Findings suggest that there was no priming effect of listening to words, whether those were related to weight or lifting contexts. Either context-related words did not prime fingertip forces for a particular action, or they did but it was abolished along with grip aperture's priming effect; just before contact. However, in Frak's study, grip force modulation on target action-related words suggests that fingertip forces can be affected by context online (Frak et al., 2010). However, the current study showed that offline, sensorimotor prediction is not affected by priming effects of language. If auditory processing of action-related words can increase static grip force for a brief temporal window, a similar, or differently scaled, modulation could potentially take place during word articulation.

3.4 Experiment 3: Control of forces during speaking

In this experiment, it is hypothesised that grip force can be influenced by speech production in a similar manner as observed during speech comprehension (Frak et al., 2010) and on kinematic measures during reaching and grasping while shouting (Fargier et al., 2012). That is, a temporary increase in grip force is expected during word articulation, and perhaps stronger on action-related verbs. Participants held an object, and in one block, read nouns and action-related verbs silently, and in the other out loud. The design of data collection allowed us to compare static grip force for individual words during and before they were either read or articulated. This study is focusing on online fingertip force control rather than planning, while the latter was only significantly affected by impact sounds but not meaningful speech cues.

3.4.1 Methods

Participants

A total of 18 self-reported right-handed individuals (13 females, mean age 20.4 years, SD = 2.5, range from 19-26) were recruited from Heriot-Watt University, Edinburgh. Assessment of handedness was performed online as a follow-up with the use of Edinburgh Handedness Questionnaire (two were unreachable). All participants had normal or corrected-to-normal vision and no motor impairments. All participants gave informed consent prior to testing, and all procedures were approved by the local ethics board.

Stimuli and procedure

A custom-written script in MATLAB (Mathworks) controlled the trial start and end cues with a short "beep", and handled the data collection from a pair of force sensors (Nano17, ATI Tech). The stimulus was one black cylinder with a 200 gram mass and volume of 7.5 cm diameter, 7.5 cm tall. The force sensors were mounted on top of the cylinder with a custom-made handle.

Participants sat on a chair in front of a large table and placed their hands on it in a relaxed manner. Stimulus was placed 35cm away from the participant along the midline of the body. The participants were instructed to lift and hold the cylinder with their right hand on the sound of the beep which indicated the start of a trial and watch the monitor placed at eye level, 70 cm away; they lifted the cylinder to a height of approximately 23 cm, equal to the height of the indicator placed next to the object. A sequence of words (22 words, 11 neutral nouns and 11 action-related verbs, counterbalanced for each participant) was presented within three seconds of the lift, with a duration of one second each, and one second blank screen between stimuli. One syllable words were selected to keep the word duration as similar as possible, controlling for frequency but not for number of letters as the rest of the available words with equal letter numbers had a low frequency rate. Example nouns, '*door, floor, van, glass…*' and example action-related verbs, '*push, pull, squeeze, pinch…*'. The participants would either read the words out loud, or silently read them depending on the condition, instructed by the experimented before each block of words. Conditions were reading aloud (RA) and silent reading (SR), alternating, with eight RA and eight SR blocks for each participant. Each block featured the same 22 words in a random order. The experiment lasted for about 40 minutes.

Sensors recorded 3D forces at 500 Hz, and the data were smoothed with a low-pass Butterworth filter with a cut-off frequency of 14 Hz. The laptop's internal microphone was connected to MATLAB with a custom-script to provide immediate audio data in the form of vectors (analog input) and was time-locked with the force sensor data collection script. This allowed us to locate the initiation of word articulation, extract its index ('when' it happened) and use it as a reference point to select the relevant grip force data of that particular temporal epoch. The length of all selections was consistent with the longest articulated word, in this case, 350ms. To simplify, the last 350ms before word articulation was a baseline trial, and 350ms from the moment of word exposure until 350ms have passed were used as templates. As a result, each baseline section was 350ms long. Each word exposure section was 350ms long and time-locked (SR), while each word articulation section was 350ms and dependent on the start of the articulation as detected by the microphone data, and indicated by the moment the audio data changed to an abrupt increase in dB. Words were sorted, with each word belonging to one of the two conditions (Reading Aloud, Silent Reading) two levels of word type (Noun, Verb) and two levels of epoch (Baseline, Exposure). These dependent variables were analysed with a 2×2×2 repeated measures ANOVA.

3.4.2 Results & Discussion

Online force control

There was a significant effect of Condition ($F(1, 17) = 19.27$, $p < .001$, $\eta_G^2 = .429$), but not an effect of epoch ($F(1, 17) = 1.27$, $p = .28$, $\eta_G^2 = .036$). A significant effect of Type was found ($F(1, 17) = 4.67$, $p = .045$, $\eta_G^2 = .182$) albeit minor in magnitude. There was no interaction between Condition and Type ($F(1, 17) = 2.42$, $p = .14$, $\eta_G^2 = .074$; Figure 19), Condition and Epoch ($F(1, 17) = 0.18$, $p = .67$, $\eta_G^2 = .009$), or Type and Epoch ($F(1, 17) = 0.01$, $p = .95$, $\eta_G^2 = .002$).

Pairwise comparisons showed that participants increased static grip force during RA compared to SR (M = 4.55 N vs. 4.27 N; $p < .001$). They also showed a marginal increase, yet significant, during action-related verbs over nouns (M = 4.42 N vs 4.40 N; $p = .045$).

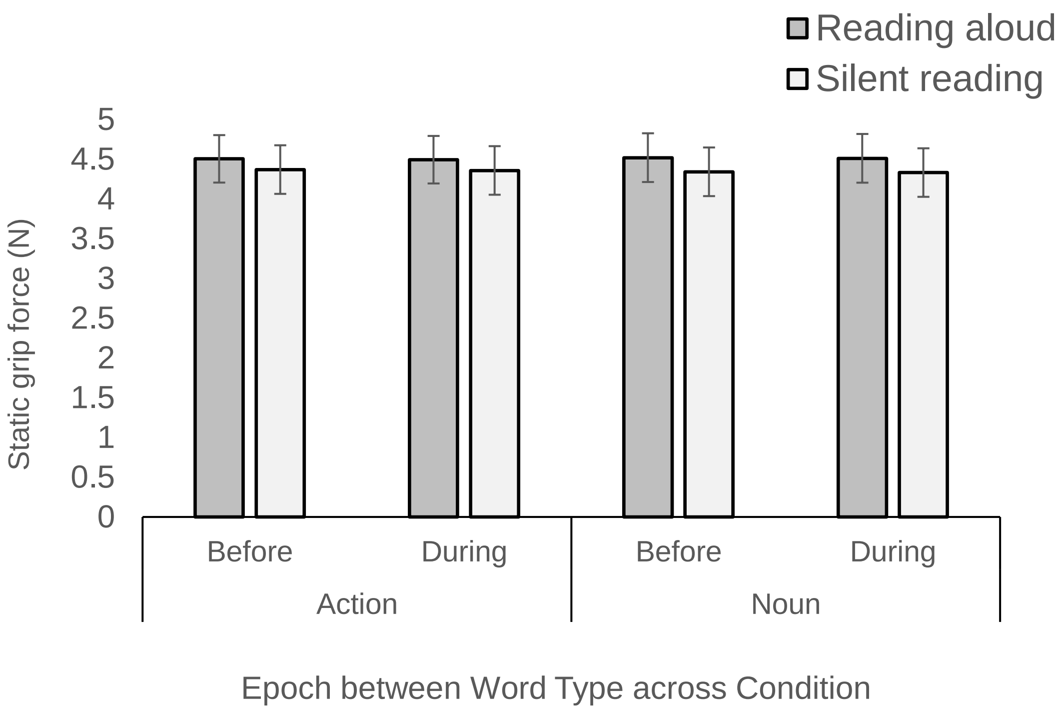

Figure 19. The means of static GF values for each Epoch across Word Types, and between Conditions

Results from the experiment show a significant difference between reading aloud and silent conditions and a marginally significant difference between word types. Indeed, static grip force was higher during word articulation when compared to reading silently, and action-related verbs caused a minor increase in static grip force. While the main effect of word type is of lesser significance due to its magnitude, the effect of condition was the important finding from this study. Using speech, regardless of word meaning, significantly influences the grip force application on an object. Specifically, on average, participants exhibited an "articulation cost" of approximately +0.3 N when reading words aloud compared to when reading them silently. The significant yet minor static grip force increase of +0.02 N during action-related verbs can be attributed to the similar phenomenon as observed in Frak's auditory input study (2010), but with a largely diminished effect on the motor system. It is important to clarify that this effect does not seem to arise specifically during word articulation, but throughout the "reading aloud" block, since there was no main effect of Epoch or an interaction. As observed in Chapter 2, Experiment 4, the effect of task instruction may be contributing to this effect. Evaluating the results of the current study in conjunction with Frak's findings, it appears that word articulation overrides the context effect of the words to a certain degree and is influencing static grip force alone. From a more generic perspective, the results suggest that when speaking out loud, we tend to apply additional force for the duration of speaking. To simplify, this additional force application is not automatic, otherwise it would be absent between word articulations.

The brain's hand area may be activated for hand-related contexts, but this activation apparently expresses itself in specific ways depending on the type of task, and shows a robustness against online modulation. Even if the hand area is activated for hand-related words, visuospatial processing is not enough to show cortico-spinal excitation for the hand area as reported in an older study (Flöel et al., 2003). Another study, specifically under a fingertip force application paradigm, showed increased cortico-spinal activation as the perceived object size was increasing (Buckingham et al., 2014). This finding alone is sufficient to hint to the specificity of the fingertip force system and warrant a real-time study on fingertip force modulation under an action observation paradigm.

The hypothesis in the next two experiments is that the kinematic cues of the actor's lift are expected to be strong enough to affect the preparation and execution of fingertip forces, increasing static grip force application during the observed lifting, especially when the observation is of a larger object than the one held. In the first experiment, participants lifted and applied static force on an object while exposed to videos of an actor lifting objects of various sizes and weights. It was asked if observing an actor lift different object sizes and/or mass, can modulate the static grip force applied by participants on their, unchanging in terms of size or mass, own object. A decrease in static force when the video's actor lifts a smaller object was expected, a similar static grip force when the actor lifts the same sized object, and an increase when he lifts a larger one. It is also expected to see the same trend with the mass alterations (lighter, same, heavier). The kinematic cues on mass alterations, such as a slower lifting motion that would otherwise indicate a heavier object, were eliminated as the actor practiced lifting all objects 15 times before the start of the experiment. This ensured that he could lift all objects in the same manner and timing, regardless of object mass. In simple terms, the actor became an expert, compared to novice, a condition that makes kinematic cues unavailable to the participant, such as the speed of lifting. However, the participant was still able to detect kinetic information, such as muscle contractions, especially the contraction state of the grip. This allowed to infer whether a potential grip force modulation would arise only from grip contraction cues.

Keeping the setup as similar as possible, in Experiment 2, video viewing was replaced with the experimenter lifting the object in real time after every participant's lift became stable. An additional size level was added, where an even larger object could potentially show whether the effect happens only on the largest of a set or on any increment above the object of equal size. Kinematic trajectories of the experimenter's hand were recorded and used as a reference for certain events. With this information available, the participant's static grip force during individual components of the lift was compared across the various levels of size.

3.5 Experiment 4: Control of forces during action observation: Video

3.5.1 Methods

Participants

A total of 18 self-reported right-handed individuals (7 females, mean age 22.3 years, SD = 2.2, range from 19-29) were recruited from Heriot-Watt University, Edinburgh. Assessment of handedness was performed online as a follow-up with the use of Edinburgh Handedness Questionnaire. All participants had normal or corrected-to-normal vision and no motor impairments. All participants gave informed consent prior to testing, and all procedures were approved by the local ethics board.

Stimuli and procedure

A custom-written script in MATLAB (Mathworks) controlled the trial start and end cues with a short "beep", and handled the data collection from a pair of force sensors (Nano17, ATI Tech). The stimulus for the participant was one black cylinder with a 275 gram mass and volume of 7.5 cm diameter, 7.5 cm height. The force sensors were mounted on top of the cylinder with a custom-made handle. The stimuli that the experimenter handled were three cylinders (5 cm, 7.5 cm, and 10 cm diameter, all 7.5 cm height) with three different masses each (140 grams, 345 grams, and 550 grams). In total, nine videos of three seconds duration each were filmed, each one showing the experimenter's arm reaching, lifting, and holding one object out of the nine size/mass configurations (90 trials, 10 trials each mass/configuration) (Figure 20). To become an "expert lifter", the experimenter lifted each object 15 times prior to filming. This practice removes the effect that size has on kinematic lifting parameters such as the lifting speed; a cue that if observed by the participants can inform them of the object's mass (Buckingham et al., 2014).

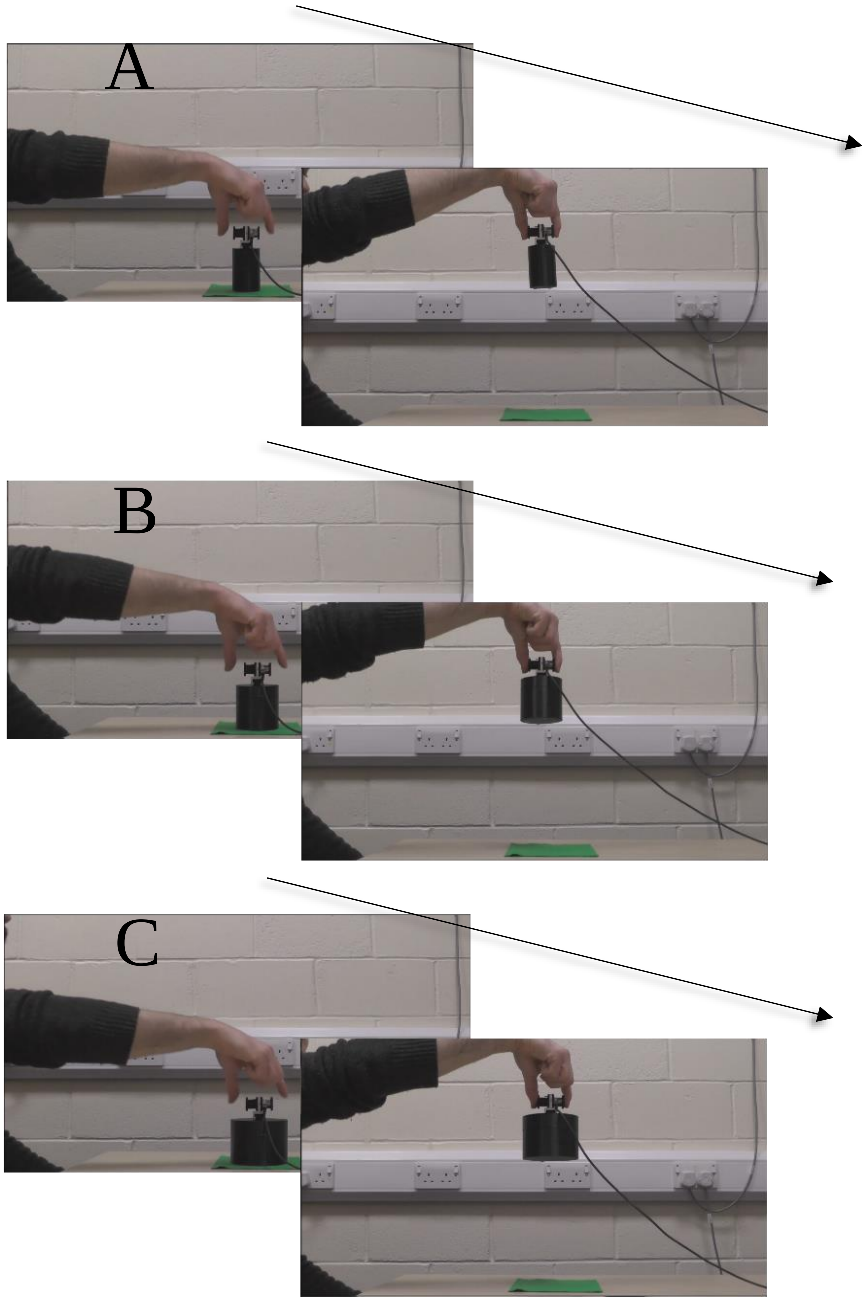

Figure 20. Video stills showing two frames of each video featuring a different size. This is the participant's viewpoint.

The setup was identical to Chapter 2, Experiment 1. Participants were instructed to lift the object on the table at the sound cue, and hold it at a level indicated by a height marker until they heard the second sound cue (7 seconds duration), returning it to the table. Each video was initiated on the beginning of the 4th second of each trial, thus leaving the first four seconds for object lift and stabilisation. Data were extracted from three key events within a trial; from 2.80 to 4 sec, from 5 to 6.20 sec, and from 6.20 to 7.40 sec. Respectively, these ranges reflect the following epochs: Before Video (1.2 sec duration until video starts playing), During Lift (during video playback, 1.2 sec until the moment the object reaches maximum elevation), After Lift (1.2 sec from the moment object is held still until end of trial).

Static grip force data from each epoch were averaged and analysed with a 3×3×3 repeated measures ANOVA under the 3-leveled factors of Size (Smaller, Equal, Larger), Mass (Lighter, Equal, Heavier), and Epoch (Before Lift, During Lift, After Lift).

3.5.2 Results & Discussion

Online force control

There was no significant effect of Epoch ($F(2, 36) = 2.39$, $p = .11$, $\eta_G^2 = .076$), no main effect of Size ($F(2, 36) = 2.91$, $p = .07$, $\eta_G^2 = .092$), and no main effect of Mass ($F(2, 36) = 0.75$, $p = .48$, $\eta_G^2 = 0.87$). Similarly, no significant interactions were found between Mass and Size ($F(4, 72) = 1.7$, $p = .16$, $\eta_G^2 = .031$), Mass and Epoch ($F(4, 72) = .59$, $p = .66$, $\eta_G^2 = .023$), or Mass and Size and Epoch ($F(8, 144) = 1.07$, $p = .39$, $\eta_G^2 = .049$). However, there was a significant interaction between Size and Epoch ($F(4, 72) = 5.31$, $p < .001$, $\eta_G^2 = .102$; Figure 21). Post hoc analysis revealed that participants used more force during the After level of Epoch when viewing the Larger object than when viewing the Smaller one ($M = 4.85$ N vs. 4.63 N; $t(56) = 2.69$, $p = .02$; Figure 22).

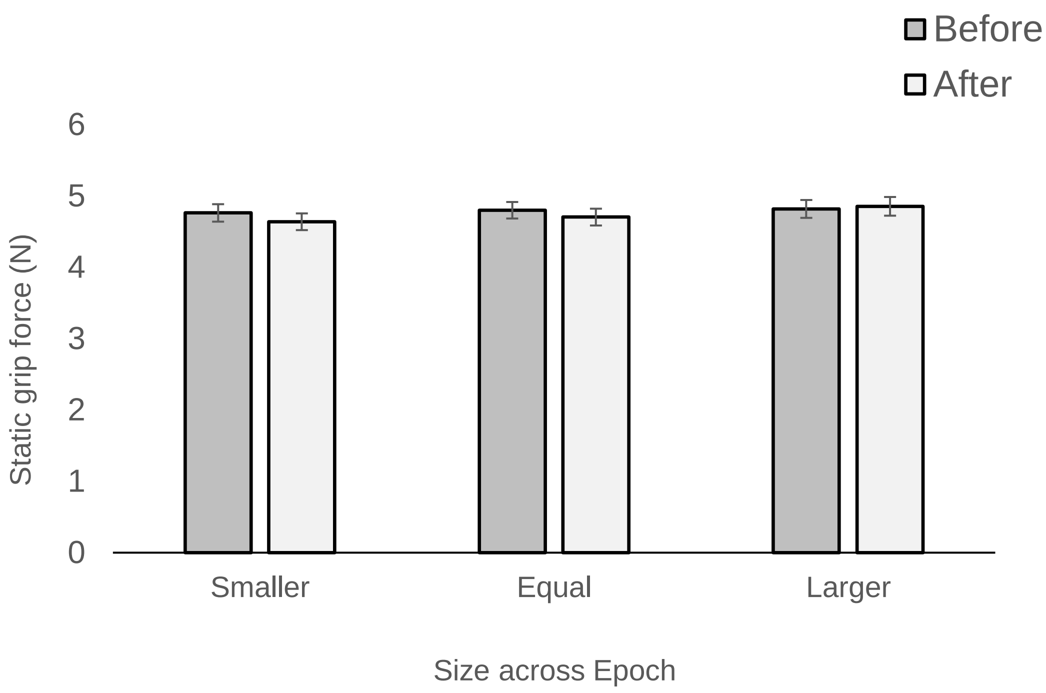

Figure 21. The means of static GF values for each Epoch across Masses

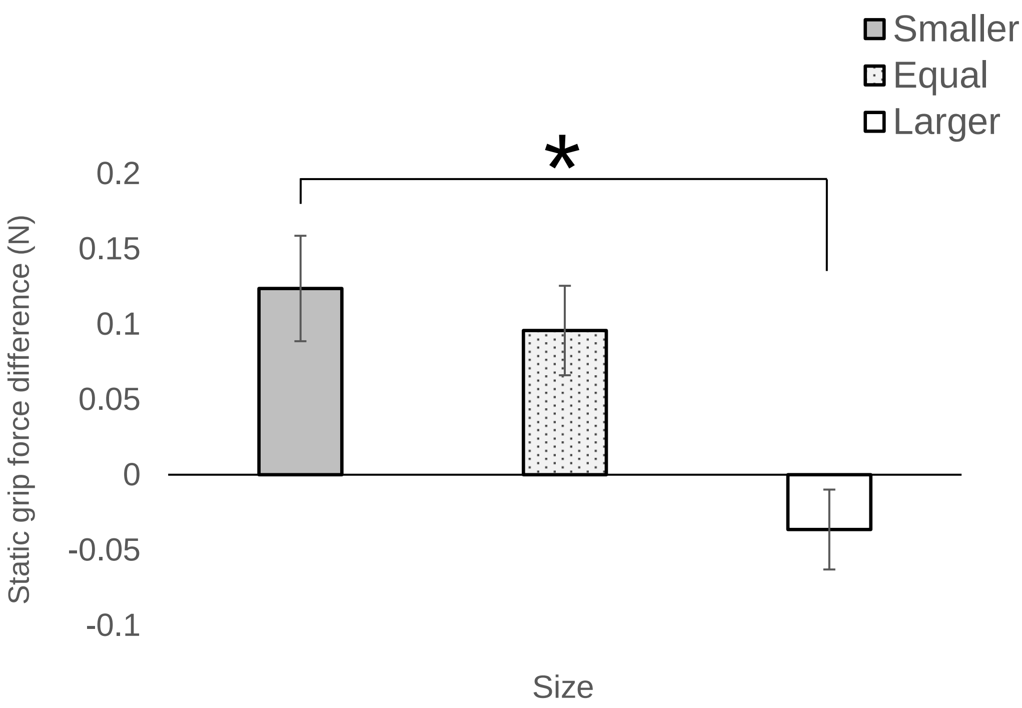

Figure 22. Static GF differences between Epochs (Before and After video viewing) for each Size viewed (Mass collapsed across groups)

The results suggested that mass perturbations had no effect on static grip force, in any combination of size. Results, comparisons between before and throughout viewing each lift, show a similar pattern of linear force decrease as found in Chapter 2 and 3 for both smaller and equal sizes lifted. For simplicity, this pattern will be referred to as "optimisation" hereafter, as it likely that grip force application is being optimised to expend the least amount of resources while maintaining a secure grip. However, there is no such effect when viewing the larger object being lifted, with participants applying the same force as they did during baseline. The absence of this effect possibly indicated a "cost" as it was present in the smaller object.

3.6 Experiment 5: Control of forces during action observation: Actor

As the design of the previous experiment was focused on replicating a video-viewing setup while testing for online force modulation, it was limited in its power to provide an understanding of a real-time application of action observation. In this study, the experimenter lifted objects physically in front of the participant who was already holding one. Additionally, to see if any specific phases within the experimenter's lifting components were more important than others, or if this reduction observed in this study is gradual and linear, the levels of Epoch were increased. There was also one more addition to the levels of Size, with an even larger cylinder, to further understand if the larger gradients are causing a higher static grip force progressively, or if this lack of gradual decrease is similar for both larger sizes. However, the factor of Mass was removed, as it did not add anything in the last experiment, and as such, could only add noise to the current one. The design of this experiment is aiming to test if action observation works when we observe a physical person rather than videos.

3.6.1 Methods

Participants

A total of 21 self-reported right-handed individuals (mean age 24.3 years, SD = 5.3, range from 19-36) were recruited from Heriot-Watt University, Edinburgh, comprising of 8 males and 13 females. Assessment of handedness was performed online as a follow-up with the use of Edinburgh Handedness Questionnaire (one was unreachable). All participants had normal or corrected-to-normal vision and no motor impairments. Two participants took part in Experiment 1. All participants gave informed consent prior to testing, and all procedures were approved by the local ethics board.

Stimuli and procedure

Participants sat comfortably in a chair facing the actor who was located at the other side of the table (1m away). They were instructed to lift the object that was located close to their right hand at the sound cue and hold it at a level indicated by a height marker until they heard the second sound cue. During this holding phase, the actor reached out and lifted an object that was located close to his right hand. The participants were instructed to observe the motion of his hand, and the lift itself, explicitly stated “watch my hand and the object being lifted”. On the second sound cue, they both returned the objects to their initial positions on the table.

The experimental setup was similar to the previous experiment, but instead of a monitor, the actor sat across the participant, facing his left. Participants kept their eyes closed, opened them on the sound cue, reached out, and lifted their object. Once the object was judged by the actor to be stable, he lifted his own object and held it at the same height with the participant’s until the second auditory cue (8 sec trial duration total), at which point both returned their objects and the participants closed their eyes. The actor wore an infra-red reflective marker on the wrist of his right hand to record his hand’s trajectory with a 3-camera ProReflex system (Qualisys) at 240Hz. The extracted Z-axis (vertical) displacement was then used to mark the timestamp of each epoch, reflecting distinct parts of the reach. There were five levels under the factor of Epoch and they were reflecting the average static grip force for a set duration (700ms) from the start of each epoch. The last 700ms before the actor reached out were regarded as the baseline (absence of actor movement), the next 700ms as the reach, the moment between when reach ended and the lift began as the grip contraction epoch, another 700ms between start of lift and end of lift, 700ms after lift ended, and an additional 700ms after the last. There were four levels of the factor Size, one for each cylinder size (5cm, 7.5cm, 10cm, 12.5cm diameter, 7.5cm height). The participants lifted the same cylinder (7.5cm) throughout the entire session. There were 80 trials in total with 20 for every level of Size. The actor lifted the four different sized cylinders of the same mass in a randomised order, belonging to four randomised sets for the first four participants respectively, and for every subsequent participant the sets were repeated.

The dependent variable of mean static GF was analysed with a 4×5 repeated measures ANOVA with the factors of Size (Small, Equal, Large, Larger) and Epoch (Baseline, During Reach, During Contraction, During Lift, After Lift, During Holding).

3.6.2 Results & Discussion

Online force control

There was a significant main effect of Epoch ($F(1.26, 24.03) = 4.429$, $p = 0.038$, $\eta_G^2 = .143$), no main effect of Size ($F(1.63, 31.09) = 0.128$, $p = .84$, $\eta_G^2 = .004$), and no interaction between Size and Epoch ($F(3.03, 57.65) = 1.133$, $p = .34$, $\eta_G^2 = .039$; Figure 23).

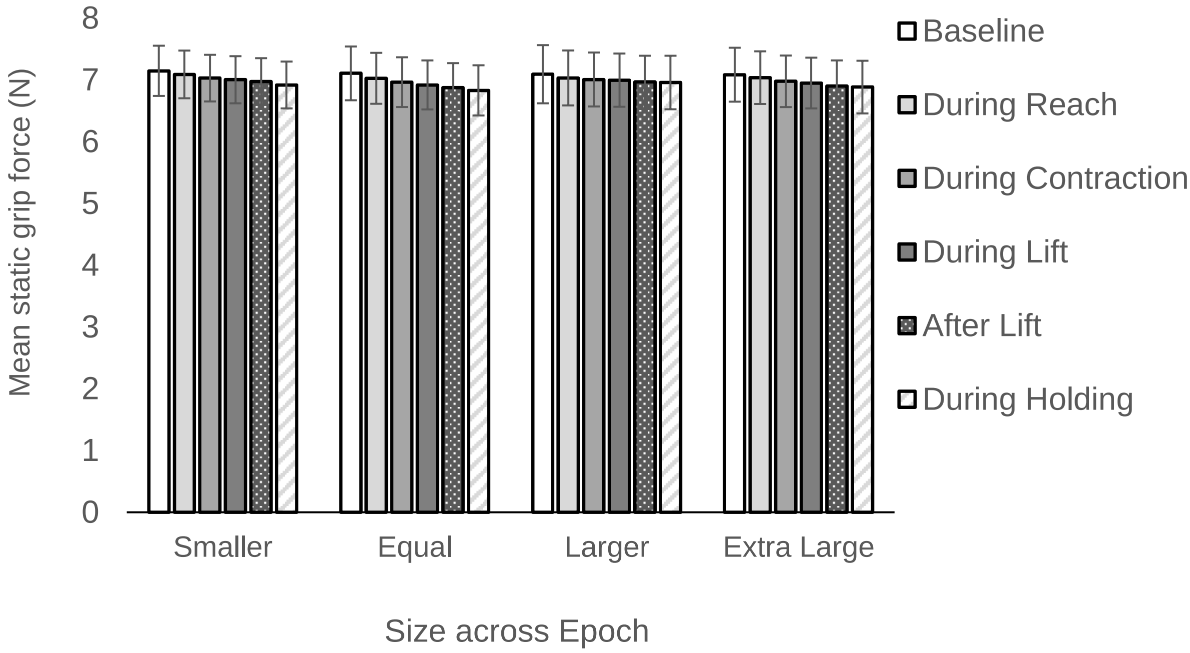

Figure 23. The means of static GF values for each Epoch across Masses

The findings from this experiment were surprising. A main effect of Epoch was found, albeit small in magnitude. This is consistent with the findings from Chapter 2, Experiments 3 and 4, all of which suggest a gradual reduction of grip force application as time progresses, akin to optimisation. It was predicted that there would be a similar lack of optimisation for either one of the larger objects, or for both. Instead, there was no interaction and thus no such effect.

3.7 Chapter 3 Discussion

It was tested to see if impact sounds and auditory processing of words can prime the fingertip force system and show force modulation, or modulate sensorimotor prediction. There was no such effect. However, in the first experiment, findings showed that participants lifted the same object faster when it caused a louder noise by dropping it from a higher point. This finding suggests that while fingertip forces alone were unaffected, sensorimotor prediction was indeed affected and influenced the participants' lifting action, but not their fingertip force application per se. It is likely that the louder impact sound created a new internal representation for the same object, as a new and heavier one. While this effect is significant, it is still localised on sensorimotor prediction rather than fingertip forces. In the second experiment, and in conjunction with previous literature (Aravena et al., 2012; Frak et al., 2010), fingertip forces and sensorimotor prediction are not primed by words, either context relevant or irrelevant. Literature shows that they can be modulated on-line, while speech is being processed. Findings also illustrate the contrast between fingertip forces and grip aperture, two crucial, functional components of a lift. While priming is measurable in grip aperture (Gentilucci & Gangitano, 1998; Glover et al., 2004) and not measurable in fingertip forces, it is important to note that both components performed their respective actions successfully without any priming effect carryover.

Setting out to find if the production of speech can affect fingertip forces, in the third experiment, participants spoke action related verbs and unrelated nouns out loud or read them silently, while holding an object. Results showed no effect of context, but an increased mean static force while reading aloud when compared to silently reading. The minor effect of word type is not taken into account for my interpretations, not only due to its shallow magnitude but also due to a lack of interaction.

The context effect is possibly diminished for one of two reasons. There is a possibility that the fingertip force system is not susceptible to influence arising from its host's functions, such as reading a motoric order out loud but without a clear, conscious, purposeful command for action. The other speculation takes into account the effect orofacial muscle activation can have on fingertip forces, as it is shown that pronunciation of syllables that involve clenching of the jaw muscles over syllables that do not, caused a significant increase in static grip force (Vainio et al., 2013). This increase may be the explanation behind the findings of this experiment, and explain the highly significant increase in static grip force during reading aloud but also the marginally significant variation between word types. In other words, the effect found in Frak's (2010) study could still be there, but it may be either masked by the effect of speech production on fingertip forces, or not strong enough in a rather “loose” setting; that is, without target words to maintain attention.

As there was no effect of Epoch, fingertip forces are not affected by the production of speech per se, but rather by the effect of instruction, as seen in Chapter 2, Experiment 4. As a result, it is possible to interpret this lack of on-line effect to an independence of fingertip forces from speech production, and the increase in static grip force during reading aloud to a preparatory effect due to task instructions. This preparatory effect cannot be attributed to the impact of multi-tasking, because in Chapter 2, Experiment 4, there was no such increase when participants were typing a word on a keyboard. Instead, it seems to be an effect of task instruction, for particular tasks that may be more taxing to force production when performed concurrently, such as tapping or speaking out loud, as observed so far.

The next two experiments aimed to find out whether the consequences action observation are measurable in fingertip force control. Considering that in the four experiments that featured measurements from multiple temporal windows within trials (2 in Chapter 2, 2 in Chapter 3) a consistent and linear reduction of static grip force was evident as the trial progressed, the lack of this force reduction can be interpreted as an effect of interest. When participants viewed a video with a larger object being lifted than the one they held, in simple words, they showed a resistance to this force optimisation over time, not apparent in the other two levels. This could be theorised to be an actual effect, perceptually affecting our action and reflecting an influence of size onto fingertip forces, albeit, in one direction. Mass variations did not contribute to any effect which suggests that hand muscle contractions are not important cues in how participants formed force predictions, in contrast to the findings by Alaerts et al. (2010). However, care was taken in each video shot to lift the objects in such a way that the timeframe and speed of the lift were identical to each mass. This could be achieved by lifting an object 15 times prior to recording the video stimuli, a number high enough to familiarise oneself with the mass and become an “expert” lifter (Buckingham et al., 2014). Thus, the lack of an effect of mass could also be due to hand contractions not being strong enough predictors of weight for the participants to modulate their forces. That is, they perceived them, but the cues were not utilised internally. Another possible interpretation is that by abolishing kinematic cues, hand contractions were not as clear predictors to inform participants, thus leading them to expect all objects of the same size as having the same mass. By asking the participants at the end of the experiment, indeed, everyone reported that they saw three sizes, but did not realise they were three masses for each size.

In contrast, expecting a similar behaviour in Experiment 5, it was surprising to report a lack of size effect. The gradual reduction was evident and with a significant main effect, but participants' force application was similar throughout all sizes, including the largest cylinder as the new addition. There is a possibility that in a common setting like this one, where a lift is observed real-time, action observation does not reach a magnitude large enough to be expressed overtly through fingertip forces. Perhaps in Experiment 4 repetitions were highly consistent, enough to elicit a force response from the participants, but not as consistent in the second to elicit the same response.

In either case, the effects were rather small, and not enough to constitute a meaningful effect of action observation on fingertip force application. The findings from this chapter seem to be consistent with those of the first chapter; fingertip force application appears to be a largely independent and isolated system which is impervious to interference from other motor programmes.

4. General Discussion

This series of experiments was devised to study what effects a set of factors reflecting common human behaviours and experiences may have on the control of our fingertip forces. The findings in this series of experiments, overall, provided further evidence that the fingertip force system in lifting and holding acted with fundamentally different sensitivities and limitations than the kinematic system in reaching and grasping is known to act with. Fingertip forces were divided into a planning phase that initiated on object contact until the first brief moment of a lift, and an online control phase that was maintained from the lift itself onwards. Throughout, it was shown that the planning and online control phases are in fact dissociable components (Figure 24). This fits well as an analogy with the same phases present in reaching-to-grasp PGA measures which operate similarly (Glover & Dixon, 2002); when online control begins to take over, fingertip forces become impervious to higher-order perceptual interactions. In some cases, fingertip forces overcompensated by applying a larger force when a concurrent task was equally engaging to holding an object, such as speaking words or tapping with the other hand.

Aside from the lack of perceptual interactions on online force control, the other factors were also unsuccessful in directly impacting online forces in an immediate way;

namely, the use of the other hand, action observation, or speaking out loud. All those factors could only impose an overall preparatory effect of fingertip force overcompensation on certain levels, maintained throughout certain blocks, but did not manage to cause an effect exclusively for the duration of their execution. In other words, it seems that the overcompensation of force was not a direct result of the given additional function's involvement, but a safety margin introduced by some level in the motor control hierarchy as a precautionary measure due to the attentional demands of a secondary task.

Bimanual effect	**Planning**	**Control**	**Comments**
Experiment 1	Lower LFR Both	Higher static GF	Unexpected finding, forces were expected to behave as their unimanual counterparts
Experiment 2	Lower GFR Right Hand	No effect	Unexpected finding, forces on the lighter object were expected to increase when the other hand was holding a heavier one
Experiment 3	-	No effect	Unexpected finding, the holding hand's forces were expected to increase when the other hand was holding a heavier one
Experiment 4	-	No effect	Unexpected finding, it was expected that different tasks performed by the non-holding hand would increase the holding hand's static GF application
Concurrent task effect			
Experiment 5	Higher LFR on louder impact sound	-	Expected finding according to past studies
Experiment 6	No effect	-	Unexpected finding, planning variables were expected to be affected by context related words
Experiment 7	-	No effect	Unexpected finding, no stimulus specific increase of static GF was observed. Instead, task specific increases were noted
Experiment 8	-	Gradual reduction of static GF except during viewing the largest object being lifted	Expected finding according to "superstimulus" effect
Experiment 9	-	Gradual reduction of static GF during viewing all sizes being lifted	Unexpected finding, the effect from previous experiment was abolished

Figure 24. Summary table depicting the presence or absence of effects on each experiment. It is sectioned to account for different effects; Bimanual effects on studies 1-4, and Concurrent task effects on studies 5-9.

Bimanual coupling

Chapter 2 examined whether there was an overflow of the lifting hand's forces on the forces of the holding hand, when the former was either lifting objects or performing a series of tasks. Static grip force increased bimanually when compared with the unimanual condition, when task demands were the same for each hand. Thus, online force control overcompensated. Examining the scenario where masses differed, in Experiment 2, and expecting an overcompensation as well, a static grip force increase was not evident in the bimanual condition. Instead, in the bimanual condition, each hand's static grip force was similar to that of its unimanual counterpart. Additionally, as expected, the hand lifting the lighter object began lifting it earlier than the hand lifting the heavier one. In Experiment 3, participants lifted an equal or differently weighted object to the one the other hand was already holding. The lifting hand's forces had no measurable effect on the holding hand ones. Neither hand's lifting performance was prone to influences by the other hand executing similar tasks with equally or differently weighted objects. The aim of Experiment 4 was to replace object lifting with a much different task while the holding hand was hefting an object. Participants, with their left index finger, tapped to a casual metronome beat, tapped as fast as they could, typed a predefined word on a keyboard or rested their left hand, while holding an object with their right hand. Forces of the holding hand were only increased during the two tapping tasks. However, within those two blocks, static forces were similar before and during tapping. In simple words, the force increase was not a result of the tapping action as it was still higher before the tapping occurred. The main conclusion that can be drawn from Chapter 2 is that online control of one hand's forces on an object may not be affected by the forces of the other, but there may be coupling bimanual cost in situations where both hands lift identical objects simultaneously.

It appears that fingertip force control operates independently for each hand. Whether the tasks imposed identical or different demands for each hand, both hands performed similarly to equivalent unimanual lifts. It was surprising to see a bimanual cost when objects were identical. We do not usually see over or undershooting symmetrical targets in reaching-to-point tasks. Instead, asymmetrical targets imposing different kinematic demands, often cause this overcompensation. Perhaps the bimanual force coupling observed in Experiment 1 was of a facilitative nature (Mason & Bruyn, 2009). A potential explanation for the general phenomenon could be that issuing one robust command for both hands may be considered a facilitative shortcut for such a purpose. For example, pushing a large rock would be much more effective if both hands and arms act together as one limb. And perhaps the lack of a bimanual cost in Experiment 2, under this assumption, was reasonable because we are often handling objects that vary in force demands. These common objects range from being very fragile and requiring very little gripping strength, to being rather heavy and requiring a firm grip. With this speculation in mind, a separate force application for each can be a plausible setup; one that may have been hardwired in our motor system to avoid potentially dangerous mishaps, such as hanging from branches and moving between them without compromising the different grip forces required in each move, for each hand.

Despite being asked to lift simultaneously, there was no synchronous lifting in either mass configuration in Experiment 2. The lighter object was always lifted first, regardless of which hand held it, which was expected as participants had no means of predicting the weight of each object. There is a likelihood that lifting the lighter one first is a result of direct haptic feedback, in the absence of size cues. In that case, both hands were using roughly identical forces for two different weights, and as a consequence the lighter object had a shorter load phase duration. Participants used the same amount of force for both same sized objects, and consequently the lighter object was lifted more strongly, thus with a faster lifting rate. According to an early study, we use the weight information from the previous lift to guide our next lift when size information provides no relative weight cues (Johansson & Westling, 1984). Since there never was a case where the heavy mass was lifted earlier than the light, there may be a degree of adaptation that abolishes the ‘previous weight’ effect after several trials and renders sensorimotor prediction reliant on direct haptic cues; or we simply use the highest amount of force requirement experienced throughout the first trials, in both hands. The latter speculation may have more merit, as the former does not explain the absence of a significant effect regardless of adaptation; a difference might have still been observed from a number of trials. The findings suggest that hands were neither temporally, nor kinetically coupled. While the findings do not support a general strategy of temporal synchrony at every situation (Kelso et al., 1983), they do not support a strategy of temporal independence either (Marteniuk et al., 1984). They seem to describe a rather distinct behaviour depending on the situation. It is possible that when fingertip forces met with asymmetrical task demands, bimanual coupling was no longer facilitative of delivering an averaged out motor command, thus allowing the execution to be independently parameterised. The findings from Experiment 3, by including additional temporal situations within a holding phase, confirms this independent parameterisation between hands. It was however interesting that the holding hand's fingertip forces were decreasing over time, regardless of the mass held by the other hand. It is possible that this effect is a result of force optimisation to a level crucial for securing the grip but without exerting any additional effort. This fits well with the parsimonious model of the brain which describes the tendency of our cognitive process to allocate the least amount of resources for a particular task in order to expend as little energy as possible (Epstein, 1984). The findings of the Experiment 4 of Chapter 2 illustrate the importance of task instruction and motor preparation. Tapping with one finger in a guided, structured fashion was comparable to tapping frantically, expending as much energy as possible, in terms of static grip force compensation. However, static forces when the other hand was typing were comparable to forces when the other hand was idle, hinting that some tasks require no preparation or force scaling in anticipation. Potentially, this is an effect of task demands, whether its components interfere with particular aspects of the grasping system or not.

Cross-modal influence

While we seem apt in planning our fingertip force coordination for an upcoming task, priming does not appear to work well on grip force as observed in the studies of Chapter 3. That is, internal representation of an object's force requirements did not withstand the immediate tactile feedback. The latter seems more important for grip force scaling, while load force scaling could have been affected by previous knowledge. This was demonstrated in Experiment 1, where, regardless of mass, participants lifted the object dropped from a higher point at a higher rate when compared to a lower drop. However, no priming effect was found when words were articulated through headphones, neither lifting nor weight related words. It has been shown that lexical size cues on objects affect grip aperture to be scaled to the proportion of the described size and not the actual object's size (Gentilucci & Gangitano, 1998) but no priming effect of auditory size cues was found; neither from impact sounds nor from weight related spoken words. If we are to assume that language and sound processing can create internal representations of size similarly to how visual lexical cues can, there are two prominent explanations for the lack of priming. Either priming effects happened earlier, before contact with the sensors, or fingertip grip forces were significantly primed by relevant object sounds but not by lexical cues conveying weight or action-related meanings. As the production of speech is primarily a motoric function, it was not surprising to see the task-preparatory force increase in Experiment 3, as was seen in Chapter 2, Experiment 4. Being aware of the task constrains, one may accordingly compensate with additional force to prevent a mishap in motor coordination. This may well be a case of a trade-off between expending resources and securing the objects.

These findings do not necessarily contradict those of Frak et al., 2010. In their study, the magnitude of grip force modulation was very small, and temporally narrow. In a broader picture as seen here, there may be no observable, impactful, change of grip force as far as object interaction is concerned.

Size perturbations under action observation

Chapter 3 also asked whether watching someone lift an object can significantly interfere with online force control; a temporary increase of static grip force was expected. This hypothesis was tested, in Experiment 4, by having participants lift an object first and hold it, and watch videos of an actor lifting the same object but with nine variations; three sizes (smaller, equal to the participants', and larger) by three masses (lighter, equal to the participants', and heavier). Once again, the participants' holding phase analysis was segmented to correspond with two crucial epochs in the videos: one before the actor lifts, and another when the actor lifts and holds the object. The important finding here was a linear reduction of force between the two epochs for both the smaller and equally-sized objects, regardless of mass. However, no such reduction was noted for the larger object; static grip force was consistent before and throughout the lift. Experiment 5 replicated the design of the first, with four crucial modifications. An even larger sized object was added to see whether the effect found in Experiment 4 will increase linearly and proportionately to the size increase, or if it will be replicated similarly to the large one. Mass variations were removed as they did not contribute to any effect in the previous experiment. Videos were replaced with the actor, executing lifts in real time, and added kinematic data from his hand trajectory to indicate several components within the lifting action, to mark and analyse the participant's holding phases. Results showed, similarly to Experiment 4, force optimisation for every size observed across six different timepoints. Surprisingly, the effect was present at both the large and the even larger objects, in contrast to Experiment 4 where it was absent when the object was larger.

For action observation, findings were less clear. Experiment 4 showed a type of grip force vigilance when participants viewed a larger object being lifted. The aim of Experiment 2 was to understand which components of the lift were important to the sensorimotor system to cause a vigilance of force application and not undergo force optimisation. Findings however, suggested that static forces were impervious to size influences; static grip force showed this optimisation at all observed sizes. Due to having a person physically lifting the objects rather than a video, the findings from Experiment 2 may be regarded as more crucial to be addressed by the hypotheses. No epochs of the lift were particularly different between sizes, yet they all featured a linear gradient towards force reduction. A possible interpretation may be that fingertip force scaling is not affected by action observation to an extent that could significantly interfere with object holding. More importantly, it appears that on-line, haptic feedback overshadows the newly formed internal representations of weight. While perceived size affects expectations which in turn drive fingertip forces (Buckingham & Goodale, 2010), perceived size during action observation does not. It appears that fingertip force scaling may be a function that is isolated even further from the parameters that are so far affected by action observation such as finger abduction (Porro et al., 2007).

Conclusion

This PhD thesis explored a few commonplace behaviours that are thought to interact with the planning and online control phases of lifting and holding respectively. Typically, these behaviours are also crucial for several professions, including surgeons and fighter pilots, whose manual skills rely on fine coordination of fingertip forces. Results suggested a rather robust, impervious system that serves as a reliable tool. We may be using more force than necessary in certain situations, but it seems it is a desirable effect rather than a mishap. This additional force could be protecting us from dropping the object when we simultaneously perform an equally resource-demanding task. However, this compensatory force is very small, and in a general setting we would not expect this to make any tangible difference in the outcome of a motor-coordinated action.

So far, for bimanual interactions, the theoretical implications of the findings fit well with the theory that these phases are indeed separate, operate independently, and exclusive processing takes place within each (Jeannerod, 1984). When both hands are used for grasping and lifting, the changes in force application at certain situations may not be a result of motor overflow as previously theorised (J. A. S. Kelso et al., 1983; S. Kelso J. et al., 1979). Instead, it seems that compensatory forces between hands work in a synergistic manner towards a specific goal, much like bimanual coupling (Mason & Bruyn, 2009).

However, action observation did not seem to work as involuntarily as it was hypothesised here. We did expect a degree of force mimicry, but no such effect was present. Perhaps the fact that there is no significant, meaningful motor effect on the observer when observing action, is evidence against the notion that mirror neurons are playing any part in action execution. Consequently, it is evidence that supports the idea that action execution is a distinct process from action observation, unaffected by the feedforward loop, and potentially controlled by a different system (Fadiga et al., 1995). It is likely, according to the literature, that the sensorimotor system processes the actor's lifts, internalises the cues, but remains apt in inhibiting any actual manifestation of action execution. This interpretation is supported by findings that suggest motor areas are showing activation both on observation and execution of actions (Gazzola & Keysers, 2009), and by findings on single-neurons that demonstrated either excitatory or inhibitory responses, under action execution or action observation respectively (Mukamel et al., 2010).

While the methodology and design used in this work were ideal for an investigation into fingertip forces, kinematic measures could add another dimension to the questions asked. Hand trajectories, velocities and PGAs, as well as forces and torques, could help examine bimanual force coupling (or de-coupling) with a wider lens. Analysing torques on-line during a session can help in repeating trials when torques indicate unstable movement of a held object, thereby reducing variability of the results.

The selected analyses provided answers regarding the differences between force applications under several conditions, however, due to the pronounced differences of fingertip forces between subjects, using correlation analysis between force values would better suit an approach into this topic in the future.

While this thesis skimmed the surface, further work is suggested to include data-driven investigations into situations where accidents do frequently occur. Finding out if this independence of force coordination between hands fails could be the next step in identifying a behavioural biomarker. Affective states may be equally, if not more, important to be examined for their potential influence because there is a link between cortical excitability and grip force application which is manifested in a linear fashion as shown with rTMS (Dafotakis et al., 2008; Johansson, Lemon, & Westling, 1994). It is important to ask if cortical excitability is a factor that determines this independence, or if its reduction and subsequent grip force reduction are unrelated to bimanual coordination performance. As there are age-related changes in grip force application, individuals over 60 years would be an ideal population to answer the same questions (Cole, Rotella, &

Harper, 1999). If grip force application increases roughly after 60 years of age, we can test to see whether fingertip force coordination follows a pattern of change as well.

Publications

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Appendix

The appendix contains the raw code from the MATlab file used in Experiment 3 of Chapter 3. It creates a GUI featuring editable parameters such as trial duration, slide exposure duration, as well as a file selector to choose a text file containing a list of words to be displayed in sequence. The code retrieves analog input data from the force sensors, as well as send analog output to infrared cameras as a trigger to begin recording simultaneously with the start of each trial (not used in this Experiment). The GUI also plots GF after each trial for a rough error check by the experimenter.
The code for the other experiments was similar to this, using fewer functions and parameters.
When creating a Matlab GUI with the in-built guide, a singleton GUI is created with several functions and callbacks pre-built. In this Appendix, I include only those Callbacks that are functional, that is, callbacks that refer to specific buttons or textboxes on the GUI. Each section has a relevant heading in **bold** that summarises the function.

```
function varargout = PanChapter2(varargin)

% PanChapter2 MATLAB code for PanChapter2.fig
%      PanChapter2, by itself, creates a new PanChapter2 or raises the existing
%      singleton*.
%

global foldername;

set(handles.ftdispdir, 'String', 'C:\Users\McLab\Documents\MATLAB');
foldername='C:\Users\McLab\Documents\MATLAB';

%set(handles.Samplerate, 'String',num2str(1000));
%set(handles.seconds, 'String', num2str(4));
global samplerate
```

```
global ftseconds

samplerate = 250;
ftseconds=60;
daqregister('nidaq')
```

GUI RECEIVES SAMPLE RATE

```
function Samplerate_Callback(hObject, eventdata, handles)

% Hints: get(hObject,'String') returns contents of Samplerate as text
%        str2double(get(hObject,'String')) returns contents of Samplerate as a double

global samplerate;
samplerate = str2double(get(hObject, 'String'));
```

GUI RECEIVES TOTAL NUMBER OF SAMPLES (and then divides it by Samplerate to yield Seconds).

```
function Totalsamples_Callback(hObject, eventdata, handles)
% hObject    handle to Totalsamples (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of Totalsamples as text
%        str2double(get(hObject,'String')) returns contents of Totalsamples as a double


function seconds_Callback(hObject, eventdata, handles)
% hObject    handle to seconds (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of seconds as text
%        str2double(get(hObject,'String')) returns contents of seconds as a double
```

```
global ftseconds;
ftseconds = str2double(get(hObject, 'String'));



function Filename_Callback(hObject, eventdata, handles)
% hObject    handle to Filename (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of Filename as text
%        str2double(get(hObject,'String')) returns contents of Filename as a double

global savefile
savefile = get(hObject, 'String');



% --- Executes on button press in applyset.
function applyset_Callback(hObject, eventdata, handles)
% hObject    handle to applyset (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
```

SETTING THE PARAMETERS IN GUI MEMORY

```
global ai;
global samplerate;
global totalsamples;
global ftseconds;
global trial1;
global error1;
global ao;
```

%GREY-OUT THE “RUN” AND “APPLY” BUTTONS WHILE APPLYING SETTINGS

```
set(handles.runtrial,'Enable','off');
set(handles.applyset,'Enable','off');
%END
```

%SET TRIAL TEXT BOX TO 1

```
trial1=001;
set(handles.trial, 'String', num2str(trial1));
%END
```

%CALCULATE TOTAL NUMBER OF SAMPLES PER TRIAL (SAMPLE RATE MULTIPLIED BY

%TRIAL DURATION IN SECONDS)

```
totalsamples=samplerate*ftseconds;
%END
```

%***PREPARE DAQ, ANALOG INPUT, AND SET THE SAMPLING***

%PARAMETERS

```
daqhwinfo;
out = daqhwinfo;
out.InstalledAdaptors;
   ai=analoginput('nidaq','Dev1');
   %ao=analogoutput('nidaq','Dev1');
   get(ai);
   addchannel(ai, [0:5]);
   addchannel(ai, [16:21]);
   %addchannel(ao, [0]);
   %trigon=255
   set(ai.Channel, 'InputRange', [-10 10]);
   set(ai.Channel, 'SensorRange', [-10 10]);
   set(ai.Channel, 'UnitsRange', [-10 10]);
   ai.SampleRate=samplerate;
   ai.SamplesPerTrigger=totalsamples;

   disp('----------Force transducers READY TO RUN')
```

```
 %config_io;
   % out = daqhwinfo;
   % out.InstalledAdaptors;
   % global cogent;
   % if (cogent.io.status~=0)
   % error('inp/output installation failed');
   % error1=1;
   % else
   %     disp('----------PLATO Goggles READY TO RUN')
   % end
%if error1==1
%    set(handles.infobox, 'String', 'ERROR - Please see command window');
%end
```

%SET TEXT BOX TO "READY" TO INDICATE THAT EVERYTHING LOADED PROPERLY

```
set(handles.infobox, 'String', 'Ready');
%END
```

%SET THE RUN AND APPLY BUTTONS FUNCTIONAL

```
set(handles.runtrial,'Enable','on');
set(handles.applyset,'Enable','on');
%END



%address=hex2dec('378');
%byte=3;
%outp(address, byte);
```

RUNNING THE TRIAL

```
% --- Executes on button press in runtrial.
function runtrial_Callback(hObject, eventdata, handles)
% hObject    handle to runtrial (see GCBO)
```

```
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

global ai;
global samplerate;
global totalsamples;
global ftseconds;
global savefile;
global number;
global foldername
global a;
global ao;
global Slideshowname;
global Slideshowpath;

set(handles.runtrial,'Enable','off');
set(handles.applyset,'Enable','off');



cla(handles.axes1)
cla(handles.axes2)
```

PREPARING TEXT BOXES FOR RELEVANT INFO

(CONDITIONAL STATEMENTS TO DEAL WITH NUMERICAL POINT DISPLACEMENT)

```
number =get(handles.trial, 'String');
if str2num(number) < 10
   numzero='00';
elseif str2num(number) > 9 & str2num(number)<100
   numzero='0';
elseif str2num(number) > 99
   numzero='';
end;
```

PREPARING THE FILENAME STRING

```
filename1=[num2str(foldername) '\' num2str(savefile) '_' numzero num2str(number)
'raw.txt'];
filename4=[num2str(foldername) '\' num2str(savefile) '_' numzero num2str(number)
'mic.txt'];

set(handles.infobox, 'String', 'Ready');
```

CREATING THE LOOP TO COLLECT DATA AS COMING THROUGH THE DAQ

```
a=1;
while a==1
```

CHECK TO SEE IF FILENAME ALREADY EXISTS – LOOP BREAKS IF TRUE

```
if exist(filename1, 'file') || exist(filename4, 'file')
    fprintf('File already exists, please input a different ''Filename prefix''\n and/or trial
number, and press ''Run''')
    set(handles.infobox, 'String', 'Filename exists');
    set(handles.runtrial,'Enable','on');
set(handles.applyset,'Enable','on');
    break
end
```

%SENDING TRIGGER TO CAMERAS

```
%trigger1=1
%    triggerstop=255
%    putdata(ao, triggerstop);
%    start(ao);
%    stop(ao);
%    putdata(ao, trigger1);
%    start(ao)
%    stop(ao);
%--------------------------
```

%CLEARING GOGGLES

```
%address=hex2dec('378');
%byte=0;
%outp(address, byte);
%-----------------
```

%PLAYING STARTING BEEP

```
%sound(s,44000)
%---------------------
beep
disp('Data collection started')

recorder=audiorecorder(8000,8,1);
```

POWERPOINT SLIDESHOW RUNS

```
g = actxserver('PowerPoint.Application');
g.Visible = 1;
g.Presentations.Open([Slideshowpath Slideshowname]);
g.WindowState = 3;
g.ActivePresentation.SlideShowSettings.Run;
```

MIC RECORDS

```
record(recorder, ftseconds);
```

OPENING THE GATE AND LETTING ANALOG INPUT IN

```
start(ai);
```

COLLECTING THE INPUT DATA RECEIVED

```
[d, time]=getdata(ai);
```

%PLAYING STOPPING BEEP

```
%sound(s,44000)
%---------------------
beep
```

%SHUTTING GOGGLES

```
%address=hex2dec('378');
%byte=3;
%outp(address, byte);
%----------------



stop(ai);
disp('Data collection finished')
   disp('Converting raw voltages to force and torque values')
```

%FORCE SENSOR DATA MANIPULATION AND CONVERTION FROM VOLTS TO F/T

```
%A=d(1,:);
%    B=d;
 %   C=bsxfun(@minus,A,B);

   dlmwrite(filename1, [time d], 'delimiter','\t', 'precision', '%.4f', 'newline', 'pc');



   myaudio=getaudiodata(recorder);

   dlmwrite(filename4, myaudio, 'delimiter','\t', 'precision', '%.4f', 'newline', 'pc');



%x=dlmread(filename1);

%y1=dlmread('calibration35.txt');
%    y2=dlmread('calibration34.txt');
```

```
% i = length(x);
%dlmwrite(filename2, []);



%for k=1:i
%    time1=time(k,1);

%    sensor1=y1*x(k,2:7)';
%    sensor2=y2*x(k,8:13)';

%    sensorA=sensor1';
%    sensorB=sensor2';

%    dlmwrite(filename2, [time1 sensorA sensorB], '-append', 'delimiter', '\t','precision',
'%.4f', 'newline', 'pc');
%end
%--------------------------------------------
```

%PREPARING AND PLOTTING FORCE VALUES

```
   fid=fopen(filename1);
   plots=textscan(fid,'%f %f %f %f %f %f %f %f %f %f %f %f %f\r\n', 'HeaderLines',
1);
   forplots=cell2mat(plots);

%    FX1 = forplots(:,2);
%    FY1 = forplots(:,3);
%    FZ1 = forplots(:,4);
   FX2 = forplots(:,8);
   FY2 = forplots(:,9);
   FZ2 = forplots(:,10);
%    XPLOT = [FX1 FY1 FZ1];
```

```
    XPLOT2 = [FX2 FY2 FZ2];
%    plot(handles.axes1, XPLOT)
    plot(handles.axes2, XPLOT2)
 plot(handles.axes1, myaudio);
 disp('Convertion completed')
%---------------------------------
```

%ADVANCE TRIAL NUMBER

```
number= str2double(number)+1;
set(handles.trial, 'String', num2str(number));
%-------------------
toc
```

%MAKE APPLY AND RUN BUTTONS AVAILABLE

```
set(handles.runtrial,'Enable','on');
set(handles.applyset,'Enable','on');
%----------------------------------
break



end

function trial_Callback(hObject, eventdata, handles)
% hObject    handle to trial (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of trial as text
%        str2double(get(hObject,'String')) returns contents of trial as a double



% --- Executes during object creation, after setting all properties.
function trial_CreateFcn(hObject, eventdata, handles)
```

```
% hObject    handle to trial (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



% --- Executes on button press in togglebutton2.
function togglebutton2_Callback(hObject, eventdata, handles)
% hObject    handle to togglebutton2 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hint: get(hObject,'Value') returns toggle state of togglebutton2
```

BUTTON TO SELECT DIRECTORY TO SAVE IN

```
% --- Executes on button press in pushbutton3.
function pushbutton3_Callback(hObject, eventdata, handles)
% hObject    handle to pushbutton3 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

global foldername

foldername=uigetdir('C:\Users\McLab\Documents\MATLAB', 'Select directory to save
in')
set(handles.ftdispdir, 'String', foldername);

if foldername==0
```

```
    foldername='C:\Users\McLab\Documents\MATLAB'
    set(handles.ftdispdir, 'String', 'C:\Users\McLab\Documents\MATLAB');
end


function ftdispdir_Callback(hObject, eventdata, handles)
% hObject    handle to ftdispdir (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of ftdispdir as text
%        str2double(get(hObject,'String')) returns contents of ftdispdir as a double



% --- Executes during object creation, after setting all properties.
function ftdispdir_CreateFcn(hObject, eventdata, handles)
% hObject    handle to ftdispdir (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end


function infobox_Callback(hObject, eventdata, handles)
% hObject    handle to infobox (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of infobox as text
```

```
%        str2double(get(hObject,'String')) returns contents of infobox as a double


% --- Executes during object creation, after setting all properties.
function infobox_CreateFcn(hObject, eventdata, handles)
% hObject    handle to infobox (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function displayslideshow_Callback(hObject, eventdata, handles)
% hObject    handle to displayslideshow (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of displayslideshow as text
%        str2double(get(hObject,'String')) returns contents of displayslideshow as a double


% --- Executes during object creation, after setting all properties.
function displayslideshow_CreateFcn(hObject, eventdata, handles)
% hObject    handle to displayslideshow (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
```

```
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end
```

BUTTON TO SELECT SLIDESHOW (POWERPOINT) FILE TO PLAY

```
% --- Executes on button press in selectslideshow.
function selectslideshow_Callback(hObject, eventdata, handles)
% hObject    handle to selectslideshow (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
global Slideshowname;
global Slideshowpath;

[Slideshowname, Slideshowpath]=uigetfile({'*.pptx';'*.ppt'});
set(handles.displayslideshow, 'String', Slideshowpath);
```